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Knitted fabric reinforced thermoplastic in thermoforming

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Knitted Fabric Reinforced Thermoplastic in Thermoforming

by

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Thesis Advisor: Herman F. Nied

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Finally, without the love and support of my family and my girlfriend, I would never stand a chance to be here to pursue my dream. They are my pillars of strength. This thesis will be dedicated to my family and the people helped me to come this far.

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Abstract

The research of knitted fabric reinforced thermoplastic had a great breakthrough recently. A series of simulation and analysis have been developed regarding deformation behavior and other mechanical properties. Following this train of thought, this study focuses on validation of those simulations by experimental approaches. Moreover, the best way to utilize this composite has been discussed and applied to improve the thermoforming process.

Using elastomeric material as matrix and fiberglass plain weft-knitted fabric as embedding reinforcement, the formability and flexibility of this composite is outstanding. Because this combination will not block knitted fabric when forming, it can offer more stretch than comparable fabrics. Different knitting density gives different stretchability. Based on that discovery, fabric with varying densities can be embedded in one sheet to improve the product thickness distribution when thermoforming.

1. Introduction

1.1. Review of knitted fabric reinforced thermoplastic

A number of researches had been dealt focusing on the mechanical properties of knitted fabric reinforced thermoplastic and demonstration of the forming potential of knitted fiber (Mayer J, July 1991) (Mayer J H. S., 1994). The field of formability of knitted fabric reinforced thermoplastic, however, is relatively blank for the reason that knitted fabric reinforced composite cannot fit the highly curved corner without wrinkles (Xiong-Kui Li, 2009). Some studies on deep drawing and thermoforming filled this blank. In the research conducted by Naoki Takano, the composite was made by Polypropylene sheet and dry rib-knitted fabric using compression molding. And the deep-draw forming was hemispherical dealt by a male punch (Naoki Takano, 2004).

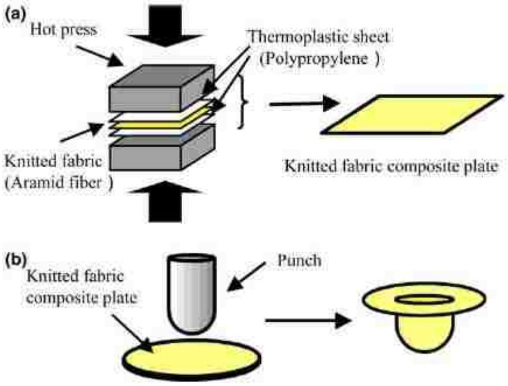


Figure 1 Deep draw forming

Khondker, Herzberg and Leong tested fiberglass knitted fabric in vinyl ester resin composites with variant of knitting patterns. The composites failed before they reached 3% strain in loading direction for both wale and course loading cases. And more interesting is, three different knitting patterns responded very similar and a different load-displacement curve than what would be expected from a knitted fabric (Khondker O.A, 2001).

Lam et al showed some data using Polypropylene and PET fibers in 2003. The fibers were co-knitted and the former material was allowed to melt to fill the voids around the latter under elevated temperature and pressure to produce composite. Although pure PET fibers could only experience a maximum of about 17% ultimate stretch, the composite was reported to give maximum elongation of 80% and 123% in warp and weft direction, respectively.

V-shape knitted fabric reinforce composites was formed and studied by Miro Duhovic et al in 2005. Made of weft knitting E-glass fiber embedded in Polypropylene (PP) matrix, the specimens were heated to 160 ℃ and formed with V-shape match dies. The test was mainly focused on shear performance during the forming. Dome shape tests were done in the same manner with rubber male punch instead of V-shape dies.

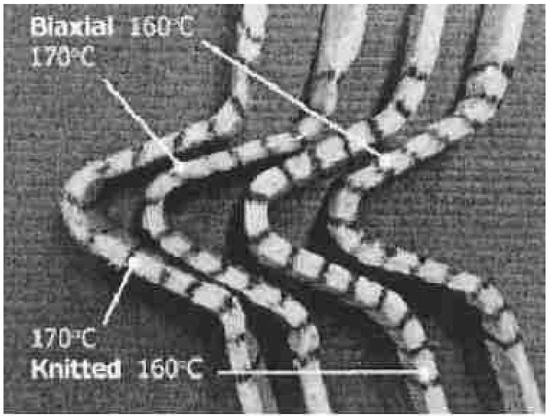


Figure 2 V-shape specimens

Within those previous researches, the doctoral dissertation of Burak Bekisli definitely needs to be highlighted simply because the results presented hereinbelow is the extension of his works. Based on this point, general review of his work will be presented here and more details will be given in context with following chapters for better understanding. The main objective of his dissertation was the analysis and better utilization of knitted fabrics reinforced composites, in a more theoretically way. To begin with, some experimental efforts were done to obtain initial data about the material. But major contribution was establishing the numerical models of its deformation behavior. As a result, nonlinear finite element (FE) analysis was developed in 3D unit cell (micro/meso scale) level and 2D global (macro scale) level to establish the deformation model of both knitted fabrics and the reinforced composite materials. The analysis and simulation was very comprehensive and also gave promising results. So based on the simulations, some innovative concepts related to the thermoforming process were investigated using the numerical models. Within limited time, no further experiments were done to verify the accuracy of these models in reality, not to mention applied new ideas on thermoforming machine.

1.2. Objective of this study

So that brings up the objective of this study; as an extension of previous research, keep using the materials and methods, explore the deformation behavior of knitted fabric reinforced thermoplastic in an experimental way. And try to compare the results with numerical models to further validate the feasibility of numerical theory. Investigate other methods of making this kind of composites if possible. Furthermore, examine the innovative idea on thermoforming machine. If obtained quite matching results to numerical prediction, the ultimate goal of this study will be establish a database for the deformation behavior of most popular fiber materials and matrix materials and their combinations, such as for example, Polyester or even Kevlar. That will certainly help to offer more options when comes to applications in the near future.

1.3. Organization of this thesis

The following chapter will be a brief introduction about thermoforming process. Since thermoforming is the platform to explore the deformation behavior of this very kind of material.

And some innovative concepts may benefit this process as well, it is necessary to have a visit on this process and also introduce the thermoforming machine that being used. The two chapters after this will talk about thermoplastic sheet and knitted fabrics, respectively. Those two materials consist the final composite therefore the chapter 5, about knitted fabric reinforced thermoplastic, is brought up. The layout of chapter 3, 4 and 5 is in order of time. Then some experimental results will be presented as well as comparison to numerical prediction as mentioned before. It will end up with a brief visit of potential applications and future prospects.

Two user manual were created and documented during this study for better references and knowledge passing. They are regarding to compression molding machine and knitting machine and will be attached in Appendix IV and V, respectively.

2. Introduction of thermoforming

2.1. Brief history

Thermoforming is one of the sheet-forming techniques have been known since the turn of the 20th century. The modern thermoforming industry, however, which regards to forming plastic sheet, started to boost after WWII. By 1950s, the demand of packaging industry stimulated the growth of thermoforming. Numerous manufacturers rapidly learned and adopted these sheet forming techniques and therefore forced the techniques to evolve. The 1960s was a milestone era that set the thermoforming industry into an ambitious pattern and defined its future trends. Roughly at that time, the specialization and separation of 'thin'- and 'thick'- gauge industries was established. When this business went into the late 1970s and the early 1980s, bold and nontraditional equipment lineups began to offer by equipment manufacturers. Starting with plastic pellet, the machinery is capable of producing finished products required little attendance. The major development in 1980s was reducing cost of the equipment allowed more people to enter into this business. General recession impacted the thermoforming industry in the 1990s. As approaching the end of 1990s and continued to move into 21st century, the digitalization is offering more precise control over the entire process which means the whole industry is entering a new era.

2.2. Industry and market

Since the beginning of thermoforming, the packaging industry has remained the highest volume user. The production of blister pack alone numbered in the millions of units for the packaging of retail goods. For food industry, there is numerous of containers made by thermoforming in take-out or retailing food packages. Transportation, medical usage, housing and construction business shared a big number of thermoforming market as well.

2.3. Process

Thermoforming is a manufacturing process where a plastic sheet is heated to a pliable forming temperature, usually 0-20℃ higher than the melting point of the material, formed to a specific shape in a mold, and trimmed to create a usable product. There are two general thermoforming process categories, thin-gauge and thick-gauge, which is defined by sheet thickness less than 1.5mm (0.06inches) and greater than 3mm (0.12inches), respectively. One obvious difference between them is thinner sheet is usually delivered to the thermoforming machine from rolls or extruder while thicker sheet is delivered by hand or auto-feed method. Typical thermoforming process involves clamping, heating, forming and cooling, and trimming. That raises the introduction of corresponding components of typical system, thermoplastic sheet, which will be given more details on following chapter, clamping mechanisms, heating systems, molds, forming forces, trimming cutters.

2.4. Components

Clamping. To carry out a successful thermoforming process, all thermoplastic sheet materials must be held securely on all four sides and through all phase of the process. There are two mechanism, clamp-frame and transport-chain, the former is widely used. There are many variations of the basic clamp-frame mechanism and all the clamp frames follow the basic frame appearance and have a matching counterframe. Usually one frame is made stationary while the other tends to open with hinges on the back side. The clamping power can be offered either by pressurized air or hydraulic forces. The Figure 3 below shows the pneumatic clamp system using in this experiment. When a sheet-fed machine is used in a continuous manner, a transport-chain system performs the duties of a clamp frame. The transport-chain system functions as the two parallel sides of the clamp frame.

The thermoforming machine being used in this research is ZMD V-223. It equipped with pneumatic clamp-frame in various length which offers multiple options. One of the most customized feature of this clamping frame design is it can be changed to any desired size, from 6”x6” up to the full size of the forming area. The clamp bars feature spring loaded pins to ensure proper holding of plastic sheet. This only require about ½” edge grip on each side. In the left of Figure 3 is a middle size clamping frame assembly with a 6” ruler for reference. In the right shows the installed four clamps.

Figure 3 Clamping system

Heating. The heat applied to this process could come from a number of sources. The two basic energy sources are gas and electricity and therefore there are three basic heating methods, gas-fired convection oven, contact heating, and radiation heating. Heating with radiation energy essentially uses infrared spectrum wavelengths and is most popular heating method among the three. There are many types of radiant heater element variations, such as, for example, open resistor, flat strip, ceramic, Pyrex glass, and quartz, each with unique differences and special characteristics. 24 independent ceramic radiant heaters installed in ZMD V-223, 12 for the top and 12 for the bottom. That feature can provide 30 Watt per square inch which is a relatively good performance compare to other thermoforming machine being manufacture at that time. The Figure 4 is the layout of the heater for both top and bottom identically.

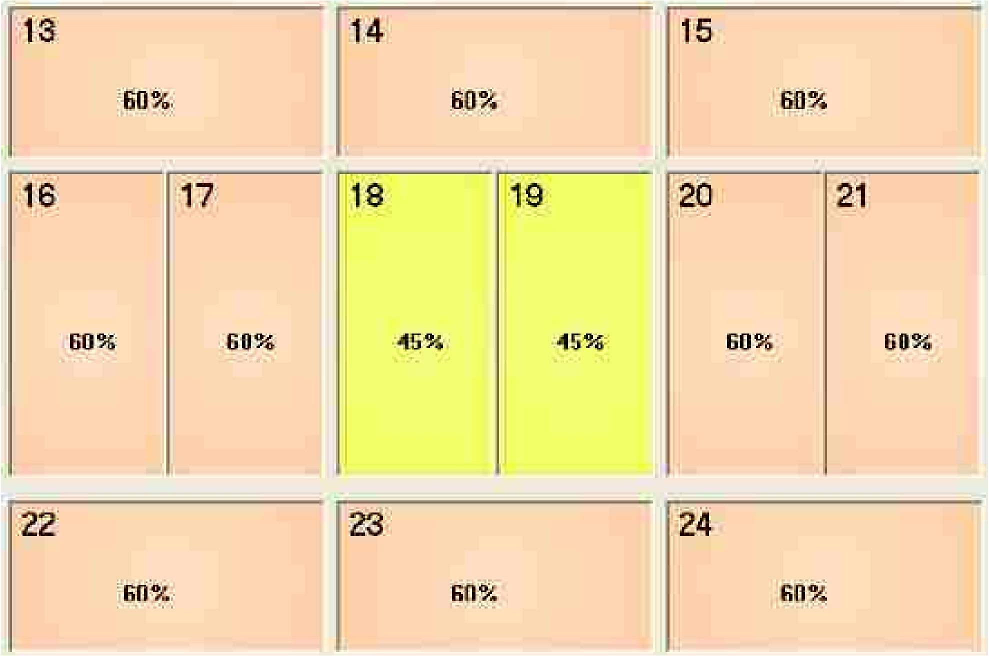


Figure 4 Heater layout for ZMD-223

Molds. The actual shaping and forming in thermoforming process are done with molds. Molds have two functions, providing a basis for the sheet to receive its shape, and cooling down the sheet. A mold made with a cavity configuration is called ‘female’ mold and it is usually shaped in an open, flared cavity form. Due to the stretching in the forming cycle, the thinning effect will cause mechanics weakness of the sheet. The deeper the mold cavity, the thinner in the side and bottom wall thickness. Therefore, with simple female mold types of forming, there is ideal depth-of-draw ratio which should be limited to 1:1. The shrinkage of materials will make the formed part smaller than the actual mold and pulls away from the mold side which cause no trouble for removal from the mold. A male mold essentially is a completely reversed form of the female mold. Instead of a cavity configuration, these molds are in the form of a protrusion. Male molds are often selected over female molds due to less costly. Only notable issue is adding sidewall tapers in the male mold design could reduce the difficulties of removal. Borrowing techniques from stamping, the matched molds are used in forming thermoplastic sheet as well. There are two types of matched molds, completely matching contoured molds and partially matching contoured molds.

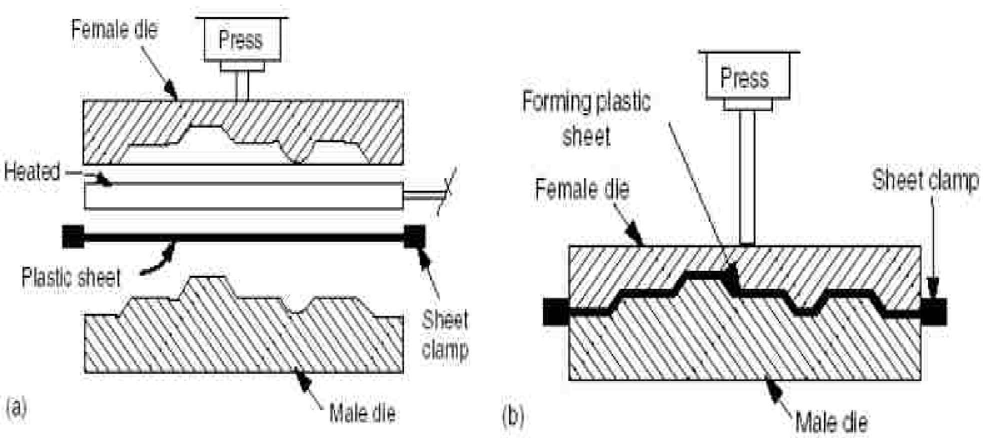


Figure 5 Match die schematic

The mold dimension and material selection should be considered following some rules when comes to mold design. Clamping frame dimensions and stroke height etc. need to be compromised in dimensional design. In terms of material selection, the period of time and light usage in this research free our hands from choosing wood, plastic and metal. Based on minimizing material cost and milling machine cost, and the need of forming, two molds are used. A 8.5”x5.5” rectangle with 1” depth cavity female mold, and its matching male mold. Both made by High-density Polyethylene (HDPE). Figure 6 is a glance of them. The drawings with more details will be attached in the following Appendix III. Venting holes also need to be considered as part of the evacuation system in the mold design. Though venting holes, vacuum pressure can apply to make sheet stick to the mold surfaces. The diameter, location and number are determined by vacuum surge tank volume, vacuum pressure, mold vacuum box volume and desired vacuum time. Since the capability of vacuum is much higher than required for this small mold, an array of 4x9 with diameter 1/32” venting holes are designed. With this level of diameter, the quality of product surface will not be affected.

Figure 6 Female and male mold

Forming forces. To shape a flat sheet form into a different form and compel it to follow the contours of the adjacent mold, outside forces must be employed. The common forming forces used are, vacuum, pressure, matched mold, and combinations of those three. Vacuum is the oldest, easily accomplished, manipulated, and controlled method in this industry. The basic principle relies on the self-sealing ability of heated sheet and trapped air evacuation by vacuum, allowing natural atmospheric pressure to fill the cavity and force the heated sheet into the evacuated space. To obtain higher forming speeds and clearly defined detail, a greater force than gentle vacuum forming can offer should be applied. Pressure forming is actually accomplished with higher air pressures and, depending on the needs, can be tuned from 10 psi to the maximum of full line pressure of the plant’s compressed air system. The use of pressure combined with vacuum evacuation can consistently guarantee the best uniformity and detail resolution to part after part. In matched mold forming, the process mimics the sheet metal stamping operation. The forming is done by the mechanical forces of the platens. There are three basic criteria that have to be met to achieve satisfactory thermoforming with this technique. The first is that the platen must have enough mechanical energy forces. The second criterion for matched molds have proper escapement for the entrapped air. The acceptable depth-of-draw ratio is the third criterion should be concerned as well. Here in this research, the conjunction of vacuum and matched mold is used.

Trimming. After the forming cycles are completed, the formed parts usually have to be trimmed out of the surrounding panel. It has to be done without damage, distortion, cracking, or tearing. The type of trimming apparatus can range from a simple hand-held knife or scissors to the most sophisticated laser beam equipment. Based on the amount of specimen in this study, there is no special need for trimming device. The composites were cut by paper trimmer.

3. Thermoplastic sheet

3.1. Thermoplastic materials

Thermoplastics are unique man-made compounds. If exposed to elevated temperatures, they become soft and eventually even liquefy, and if cooled down, they harden and set up firm. Thermoplastic polymers differ from thermosetting polymers in that they can be re-melted and re-molded. Many thermoplastic materials are addition polymers; e.g., vinyl chain-growth polymers such as Polyethylene and Polypropylene. Thermoplastics are elastic and flexible above a glass transition temperature, specific for each one. Some thermoplastics normally do not crystallize. They are amorphous plastics and are useful at temperatures below the glass transition temperature. They are frequently used in applications where clarity is important. Some typical examples of amorphous thermoplastics are PMMA, PS, and PC. Thermoplastics will crystallize to a certain extent and are called "semi-crystalline" for this reason. Typical semi-crystalline thermoplastics are PE, PP, PBT and PET. The speed and extent to which crystallization can occur depends in part on the flexibility of the polymer chain. Semi-crystalline thermoplastics are more resistant to solvents and other chemicals. The thermoplastics are manufactured from monomers, which are derived from crude oil, coal, and natural gas. These monomers will create high-molecular-weight chainlike molecules when been through high heat, pressure, and catalysts which is called polymerization. During that procedure, it can gain strong covalent chemical bonds within the independent long-chain molecules, and they have strong tangled or woven intermolecular bonds as well. The longer the molecular chains, the higher the molecular weight, and the stronger or tougher the plastic produced. The key demand in thermoplastics when used in the thermoforming is that the resin of high molecular weight with the best intermolecular entanglement available. Since the thermoforming process uses a preformed plastic sheet clamped and held only by its edges, the actual material stretching and material distribution are highly depend on that molecular relation. Initially, the thermoplastic sheet should contain molecules with maximum molecular weight to permit optimum stretching without rupturing or splitting. A fact often being ignored is that degradation and scission of molecules take place throughout the thermoforming process. Some products may not accept any recycled material without damage to their integrity.

During thermoforming process, thermoplastic will exhibit a reduction of modulus of elasticity, stiffness, and load-bearing capacity. To obtain desired products, better understanding of their properties and undermined relations is necessary. Table shows some data of typical thermoplastic materials.

Table 1 Typical thermoplastic materials

	Density (g/cm^3)	Tensile strength (N/mm^2)	Elastic modulus (N/mm^2)	Linear thermal expansion (10^{-6}/ ℃)	Transformation temperature (℃)	Crystallite melting range (℃)	Processing shrinkage (%)
PS	1.05	55	3350	75	80		0.5
ABS	1.05	50	2500	92	100		0.6—0.7
HDPE	0.95	28	1100	200	105	125+15	1.2—7.0
PP	0.92	30	1200	150	140	158+10	1.5—1.8
PC	1.2	61	2300	65	150		0.9—1.1
PVC	1.39	65	3100	63	82	100—260	0.25

3.2. Thermoplastic elastomer (TPE)

Thermoplastic elastomers (TPE), sometimes referred to as thermoplastic rubbers, are a class of copolymers or a physical mix of polymers which consist of materials with both thermoplastic and elastomeric properties. They are relatively easier to use in manufacturing compare to the mainstream of elastomers, which are thermosets. And with some clear advantages, demands and production of thermoplastic elastomers are booming nowadays. One advantage is the fact that they can be processed several times by production techniques involving heating and recycling. There are six generic classes of TPEs generally considered to exist commercially. Examples of TPE products that come from block copolymers group are Styroflex (BASF), Kraton (Shell chemicals), Pellethane, Engage (Dow chemical), PEBAX (Arkema), Arnitel (DSM), Hytrel (Du Pont) and more. The thermoplastic elastomer currently be used in the particular research is PEBAX® 2533 from Arkema. Some main ingredients include flexible polyether and rigid polyamide and the grade is specially designed to medical and food uses. The table followed can give a glance of some important features and processing requirements. More details about this material offered by supplier will be showing in Appendix I.

Table 2 PEBAX processing recommendation

Density	1.00 g/cm^3	Drying	4-8 hours/ 55-65 ℃
Melting point	134 ℃	Injection Temp	180 ℃ min/ 210 ℃ recommend/ 240 ℃ max
Vicat softening point	58 ℃	Mold Temp	10-30 ℃

3.3. Sheet making

All the known thermoplastic resins have to be converted into sheet form, by various methods, resulting in precut panels or continuous sheets which are then wound onto coiled rolls.

There are three basic sheet making methods, calendaring, casting, and extruding. In many cases, only one method can be used to make sheeting of particular material.

Calendaring is a very simple process that is easily adaptable to thermoplastics. This process, which replicates the well-established sheet-rolling and rubber sheet-making process, is the same technique as that used in mechanized pizza-dough-making apparatus. The calendars consist of a series of rollers which are rather large in diameter and heated to 325 ℉ above. A fixed gap or roller distance is set between the initial rollers and is then continuously reduced between subsequent rollers. The function of the initial two rollers is to provide for mixing, blending, heating, and metering of the softened plastic. The remaining rollers are used to size the thickness of the sheet to the final gauge required. The arrangement and array of calendar rollers vary from manufacturers and the rollers are also selected according to resin type, sheet size, feed method, and other individual requirements. One of the most frequent problems for calendaring method is that small pinhole are often manufactured in the sheet. It will be rejected for vacuum or air pressure failure.

For particular resin materials, the casting method may be the only method available for the product of sheet forms. The basic casting technique has two variations, each used for specific purposes. The first is almost always used with acrylic materials. The casting process is accomplished by pouring the base monomers, or in many instances, partially polymerized syrups or their blends into suitable sheet molds of onto moving stainless steel belts. When heat is applied, final polymerization will take place. The second type is called solvent casting. This method is used mostly with PVC. The basic resin material and the necessary additives are softened and heated in predesigned flat die. All sheet made by both casting methods are typically free of pinholes, have no hidden strains, and have equal strength in both directions of the sheet. Just like calendaring, the casting method fails to create a molecular orientation in plastic sheet.

Extrusion is by far the most common and most versatile sheet manufacturing technique for the thermoforming industry. The process always starts with the basic resin supply. The thermoplastic resin materials are introduced to the feed hoppers by mechanical pumps which lift and carry the material from a smaller box reservoir or central storage silo system. The extruder, which is the main component, receives the solid thermoplastic pellets, granules, or powders, then melts, blends, and pressurizes the resins for introduction into the die. The second section, which is called transition section, is where the solid thermoplastic particles are compressed, heated, and further compressed and liquefied. The third metering section is following, completes the melting procedure, creating a well-mixed, homogeneous thermoplastic flow. The other components include die, roller stack and the sheet-takeoff system.

The sheet used in this experiment was obtained in the form of pellets and manufactured by compression molding. Since we do not have the apparatus for any of three methods abovementioned, compression molding became the only yet easiest way to make the sheet. The compression molding machine is Tetrahedron MTP-14. By setting two steps: 1) heat up 90g pellets to 320 ℉ and hold for 25mins, and 2) cool down to 90 ℉ and keep for 5mins, that machine allows us to have up to 14” in length with approximately 1/32” in thickness for a single layer of thermoplastic sheet. The specification and user manual of the machine will be attached in Appendix IV for more detail references.

Figure 7 Tetrahedron MTP-14 compression molding machine

The material was tested in simple tension. Specimen dimensions are 18 cm length and 1.2 cm width with thickness of 1.27 mm approximately. Uniaxial tension tests for this material was performed on an Instron tensile testing machine equipped with 10 Klbs load cell and the strain rate was chosen to be 10 mm/min. Typical stress-strain curves obtained are illustrated in the Figure 8 below. Results from three specimens are given and it should be mentioned that no failure was observed before the full stroke of the testing machine is reached at around 300% stretch. A specimen was unloaded at an earlier stage to observe the unloading behavior at different deformation instants. The PEBAX® 2533 clearly exhibit very high strains as expected from elastomers and the recovery of the deformation when the specimen is unloaded is quite impressive.

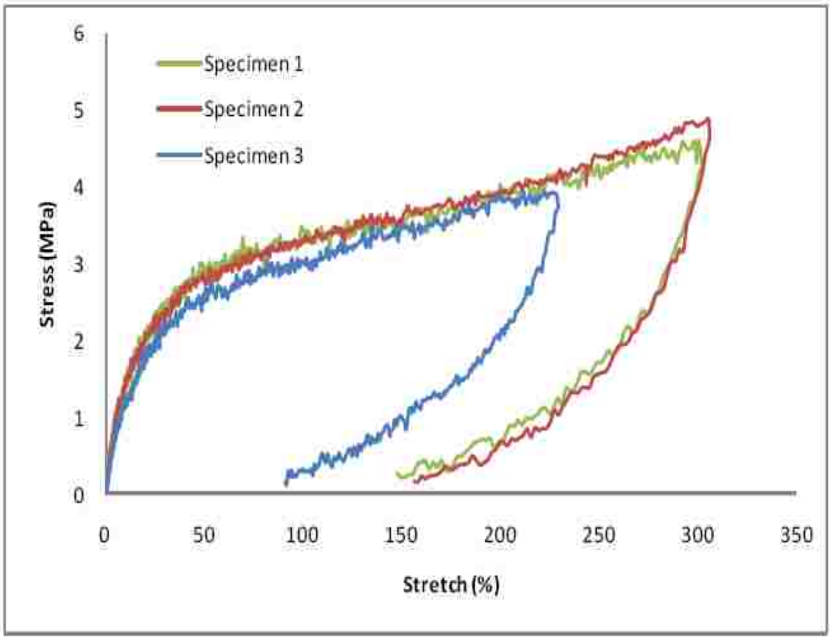


Figure 8 Tensile test results on pure polymer

4. Knitted fabric

4.1. Introduction

Numerous fabric types and manufacturing techniques have been developed in textile industry to fulfill the increasing needs. Woven, braided and knitted fabrics are the three major formations to arrange yarns to a textile fabric. There are plenty of variations within each category. For instance, woven fabric is conducted by a set of parallel yarns placed perpendicularly to another set of parallel yarns. In textile terminology, warp is used to define length and weft to width. The yarns in the warp direction are positioned over the first of the crossing weft yarns and are pushed under the next one. The one-up-one down interlacing pattern is called plain woven, like the left one in Figure 9 shown here. Variation happens when changing the frequency of the pattern. The right pattern shown in Figure 9 is an example for 8 harness satin, representing a yarn come up every eighth interlacing with the crossing yarn.

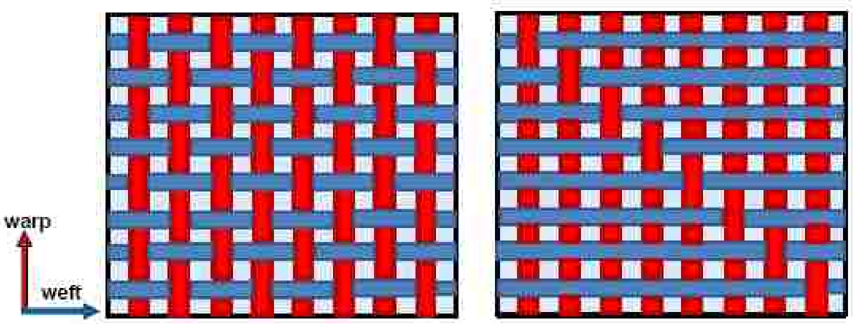


Figure 9 Woven fabrics

Braiding is similar to weaving in terms of structures. The obvious difference is yarn threads go diagonally in general. Well advanced weaving and braiding machines of today are capable of producing planar, tubular and 3D fabric with hundreds of patterns.

The remaining category is knitted fabric which is important to following chapters. Knitting is the most versatile textile forming technique and can be investigated in two major groups. Weft knitting is simply formed by a dingle yarn looping around itself and knitting process proceeds in the weft direction, or along the width of the fabric. On the other hand, warp knitting employs multiple yarns to form an interlocking chain-like structure and the formation is along the warp direction. Figure 10 compares these two knitted fabrics with a solid black line showing the loops formed by a yarn during a single knitting cycle. Also depicted in the Figure 10 is the special terminology for the knitted fabric directions, warp and weft directions are called wale and course directions, respectively. (Bekisli, 2010)

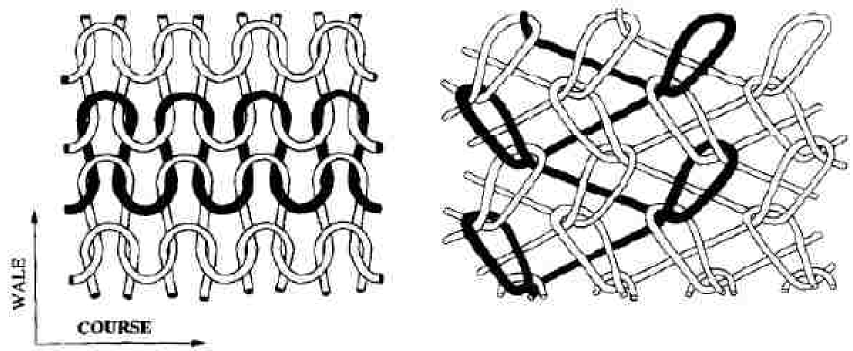


Figure 10 Knitted fabrics

In standard manufacture, special needles are placed along course direction and at a predetermined distance to each other in weft knitting. A yarn is fed by making a loop around these needles and latch mechanism attaches new course to a previously formed course by an alternation up and down motion (A.R.Horrocks, 2000). In this simple motion, the latch needle is placed inside a formed loop and move upward first. The hook at the top of the latch needle then catches the new yarn feed and a new loop is formed when this yarn is carried through the hole with a downwards motion of the needle. The process repeats until a desired number of loops are formed. The Figure 11 could help understanding the whole process. (Bekisli, 2010)

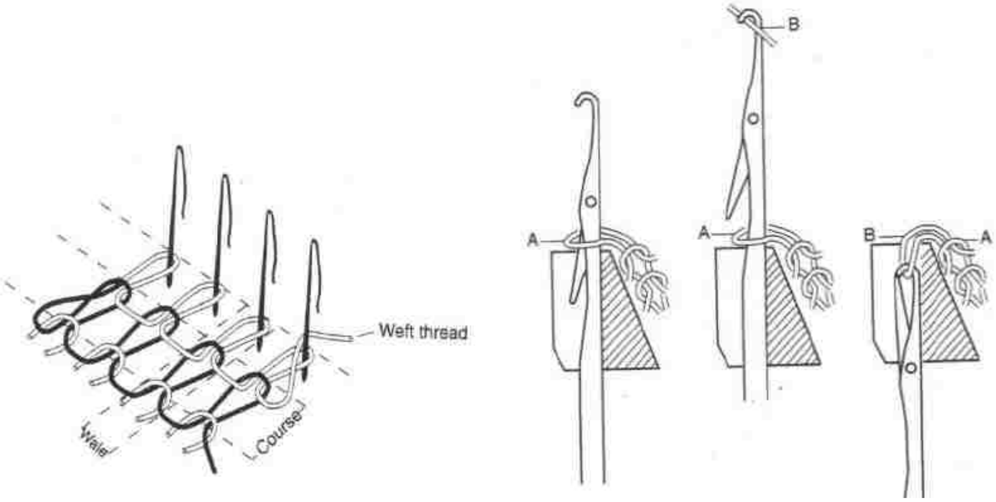


Figure 11 Knitting schematic

Warp knitting equipment, in the other hand, is fed with multiple threads therefore generally larger in size and only used for industrial applications. In the mean time, knitting machines have more flexibility on size ranging from semi-automatic personal equipment to large industrial machine so can be used for various purposes. For making foot-long fabric in this research, a Silver Reed knitting machine series number SK 840 made by Silver Seiko, Ltd. is handy to use. Its main features include 20” length, adjustable loop density from 1 (finest) to 10 (loosest), 11/64” between needles which are fixed, and even more patterns beyond in this study. The Figure 11 above shows clearly two different needles. The needles on SK 840 share the same configuration with the right one. Figure 12 is the machine from top view. User manual and troubleshooting regarding to this machine will be attached in Appendix IV for further references.

Figure 12 SK -840 knitting machine

4.2. Deformation mechanism of woven and knitted fabrics

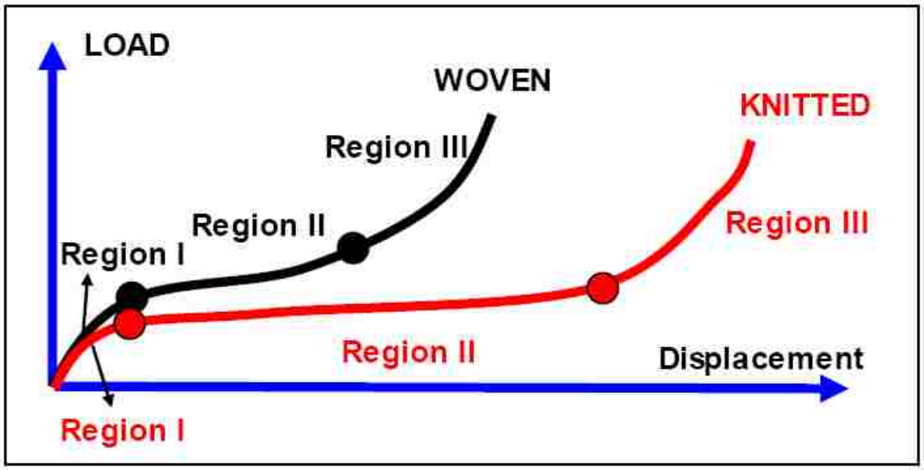


Figure 13 Deformation comparison of woven fabrics and knitted fabrics

A visit of the deformation mechanisms is good for better understanding the reason of choosing knitted fabrics as reinforcement rather than woven fabrics. Figure 13 illustrates a representation of typical deformation curves for woven fabrics and knitted fabrics. For a tensile loading case as an example, three distinct phases are expected to dominate the deformation range for both fabrics. Region-I is due to the static friction between contacting yarns and between the fibers inside the yarn as well. Most studies suggest a very small, sometimes completely unrecognizable range in this region. When this frictional resistance is overcome, the region which gives these fabrics the uniqueness in terms of deformation behavior starts. Initially curved yarns glide over each other and are bent until they are as straight as possible in the load direction. In this region, knitted fabrics may experience a very large range of stretching under small loads. Of course, a woven fabric will also have somehow similar deformation region as its initially wavy yarns will straighten and yarns will rotate over each other under a tensile load. But a biaxial stretch over 30% is only achievable with knitted fabric. Moreover, if using highly formable materials, extensions of over few hundred percent is possible. Finally in Region-III, the deformation mainly relate to fiber extension. A high tensile modulus can be obtained in this region. Some curvature will always reside due to geometrical constraints and therefore yarns could be jammed. That can trigger another deformation mechanism called transverse compression of yarns which is especially important in the strength properties of the fabric, as any kinking in the tightened loops will cause extremely high stress concentration which means fiber failure eventually.

Based on the deformation theory abovementioned, it seems fiber material can have some yet limited effect on deformation, because major extensions will happen on Region-II and have limited relation with material properties. So to begin with, we chose fiberglass due to it has been widely used especially in polymer reinforcement field. With relatively lower tensile strength, E-glass fiber, from Advanced Glassfiber Yarns (AGY), is being tested. Product number is ECG37 1/3 3.8S and please refer to Appendix for more information about it. Other kinds of fibers, such as carbon fiber or even Kevlar, are on the list for potential reinforce materials in the foreseeable future. One thing for sure is fiberglass will pave the way to other materials to explore more wonderful applications serving people.

Four sets of knit density were tested uniaxial. Photos of each specimen was analyzed using a picture editing software and wale (W) and course (C) number for each specimen had been found by averaging at least 10 digital measurements. Table 3 shows the average and standard deviation values measured and calculated for each set. Test length is 10 cm and each specimen has seven full loops in course direction. A close up picture in Figure 14 shows some clue about the tests.

Table 3 Specimen details

Set	W (loops/cm)		C (loops/cm)		W/C
	Average	Standard Deviation	Average	Standard Deviation	
1	1.62	0.05	3.47	0.17	0.47
2	1.94	0.1	4.12	0.16	0.47
3	2.3	0.11	4.09	0.25	0.56
4	2.47	0.12	4.26	0.14	0.58

Figure 14 Uniaxial tensile tests on knitted fabric

The load-stretch outcome of set number 2 shows in Figure 15. Each set of experiments showed a moderate scatter of results, which are believed to relate to manual knitting process. Although knitting manually is a good choice for low volume prototyping, skilled labor is required for repeating product quality. For better results, automatic knitting machine is recommended. (Bekisli, 2010)

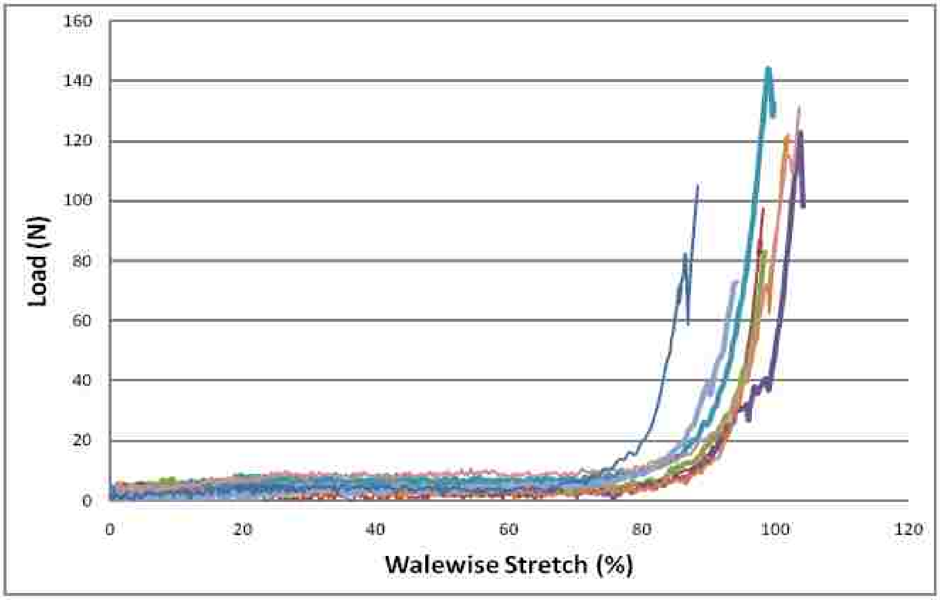


Figure 15 Tensile tests results

5. Knitted fabric reinforcement

5.1. Introduction

Two types of materials, the knitted fabrics and elastomers were discussed separately in previous chapters. In this section, the composite structures obtained by the combination of these materials will be examined in detail.

The utilization of fiber reinforcement started in military at the end of WWII. With the maturation of polymer industry in mid 20th century, fiber reinforced composite drew lots of attention due to their excellent mechanical properties with respect to their weights. Aerospace, marine and automotive industries benefited from its development first because weight reduction is highly crucial in these fields. Compare to other two fabric formations, woven fabric played a dominant role in the reinforcement applications so far. Its popularity can be explained as woven fabrics are mechanically similar to conventional continuous fibers laid in two directions perpendicularly therefore have good stiffness and strength in two main directions. On the other hand, the best utilization of knitted fabric as reinforcement will not be the cases when high stiffness and strength values from the composite are sought (X.P.Ruan, 1996). The most advantageous and unique property of knitted fabric is extensional formability. Hence, knitted fabric reinforced composite should be given full play to its flexibility. There are some examples using rigid materials as matrix, such as Khondker et al tested fiberglass with vinyl ester resin and Ramakrishna used epoxy in the same manner. The results of them consistently imply reduced mechanical properties which firmly proved the theory described earlier in this section.

Thermoplastic polymers, on the other hand, can generally provide more flexibility and will not restrain deformation of fabric loops therefore can be a better candidate of utilization of knitted fabric reinforcement. The term “Flexible composites” was introduced by Chou et al for a set of composites based upon elastomeric or rubber-like polymers. Up to a few hundred percent of deformation range make them very suitable for the outstanding mechanical behaviors of knitted fabrics when reinforced with them. In open literature, there are limited suggestions concerning the use of these materials. A uniaxial test result of polyester fabric in polyurethane matrix was presented by Huang et al. It shows the specimen could stretch to a failure strain of more than 100% in both wale and course direction as desired as shown in following Figure 16 .

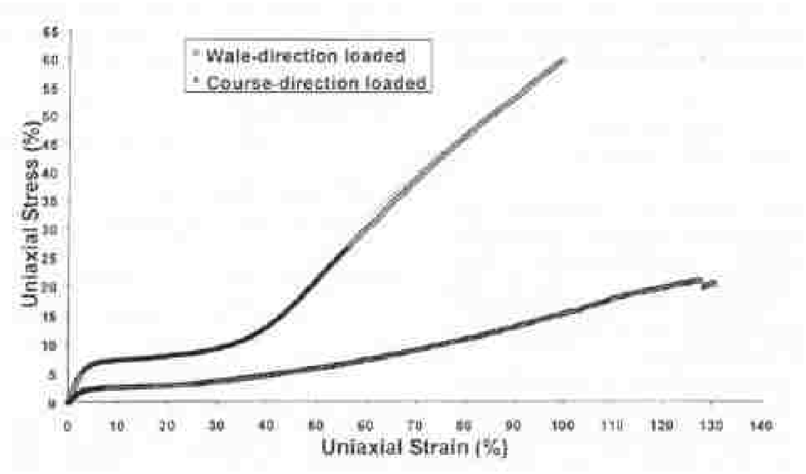


Figure 16 Tensile test results on polyester fabric in Polyurethane matrix

5.2. Experiment process and results

The basic expectation from this composite is the full utilization of the reinforcement capability of the fabric, which usually occurs after an extensive amount of deformation. As mentioned before, such large extensions can only be accommodated by a matrix material at least has the same stretchability. Thermoplastic elastomer (TPE) seems to be the ideal matrix material for that reason. It raises a question how to combine them for the best mechanical performance. The easiest way is embedding knitted fabrics in the elastomer matrix, as is typically done in other fiber reinforcement studies. By setting the same parameter with single elastomer sheet in compression molding machine, two layers of elastomer material will fill the space between yarns which lay in middle as the process goes on. The schematic layout shows in Figure 17. Due to the transparency of this matrix material, there is a very clear view of knitted fabrics in the composite, as shown in Figure 18. Each loop is quite uniform and being stretched in a hexagonal shape. Another feature that does not show in the picture but need to be mentioned is the composite is very flexible, due to the selection of matrix material.

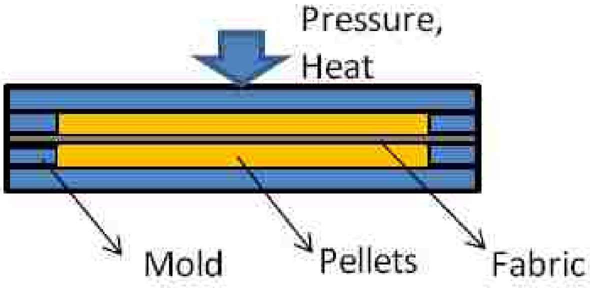


Figure 17 Schematic of composite manufacturing

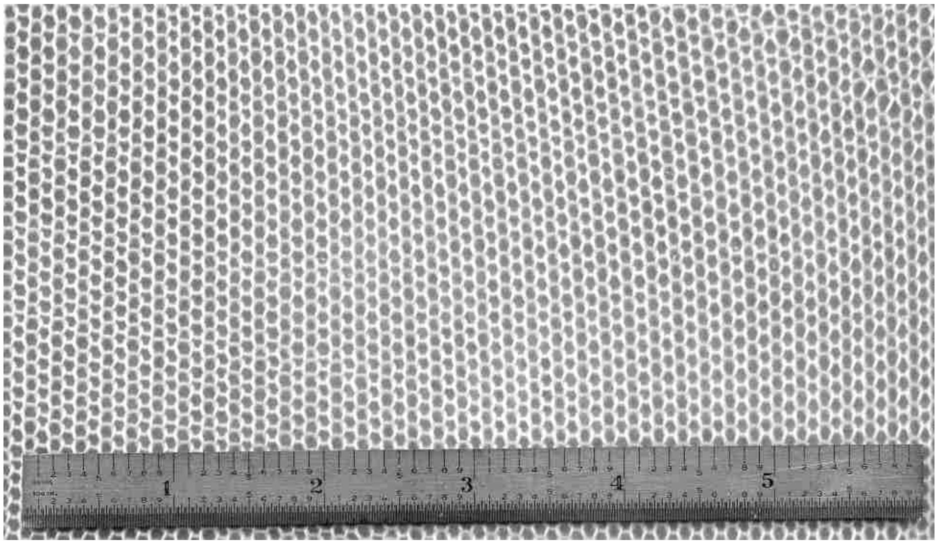


Figure 18 Knitted fabric embedded in TPE as specimen

Besides compression molding, there are other methods have the potential to manufacture this composite, such as thermoforming and extrusion. Because of the limitation on extrusion apparatus, only thermoforming method was tested. But the outcome is far away from satisfactory. The main reason causing failure is elastomer material sag too much when in the oven. There were two attampts; a) put a knitted fabric in middle of two layers of elastomer sheet, and then sent into oven. The bottom sheet would sag rapidly before reaching the forming temperature because it is only clamped around the edges. b) put knitted fabric beneath two layers of elastomer sheet. The elastomer would not sag due to the support of fabrics in this case. But when exposed to high temperature and radiant, the fabric burn out before elastomer reaches its glass transition temperature. Neither method works in some measure means making this composite by thermoforming is no chance for advancement.

The composite was cut into 18 cm by 1.2 cm for simple tension test. Transparent matrix made a clear observation of fiber movement possible during the test. A sequence of deformation is shown in Figure 19. Loading in coursewise direction is shown in the former image while the latter shows walewise. In Figure 19, the yarns inside appear to be aligning themselves in the loading direction. There are some data generated during the tests in form of curve. The results in first graph clearly show that the deformation range of the composite was not dramatically lost. The local failure did not lead to ultimate failure and the elastomer still carried the load in the fabric-failed regions. This allowed the specimen to stretch further while other regions of the fabric failed in succession.

Figure 19 Several stages of tensile test

The results indicate that the elastomer-based composite with embedded knitted fabrics can be used especially in energy absorption application. Even with single layer of knitted fabric, as can shown in Figure 20 (c), the strain energy, i.e. the area under the stress-strain curve, is largely enhanced when compare to the elastomer-only case. A multilayer reinforcement system, with possibly different knitting patterns in each layer and thus different failure stretches, would naturally make the composite more effective in terms of energy absorption capacity. (Bekisli, 2010)

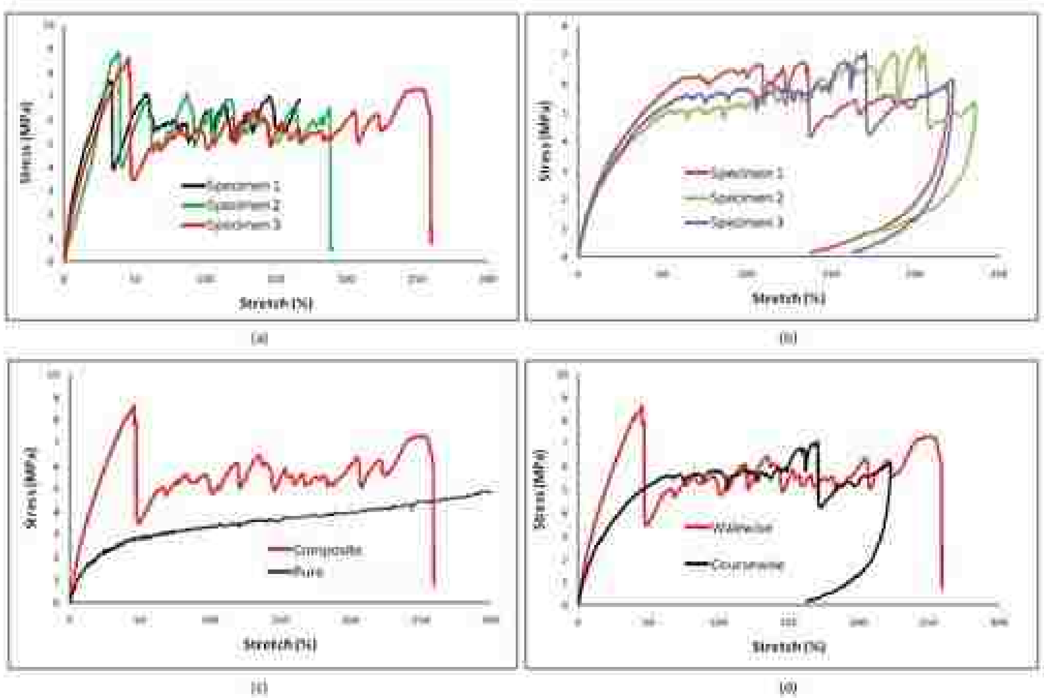


Figure 20 Stress-stretch curves: (a) walewise loading, (b) coursewise loading, (c) composite vs. elastomer, (d) walewise vs. coursewise

5.3. Thermoforming optimization

Thermoforming is widely used in polymer processing, especially if the product is large in dimensions. And other advantages like relatively lower initial tooling cost or lower design-to-market time make thermoforming very suitable for prototyping or low volume production.

As described in previous chapter, the process starts with heating up the polymer sheet above its glass transition temperature to the sheet turns into rubbery state. The following step is to retrieve from oven and apply forming force to desired shape. Though seems simple in theory, the process might be difficult to control and may require skilled labor for consistent quality. One of the most crucial issues of thermoforming process is the variation of thickness on different regions of the final product. Due to the fact that regions of formed plastic experiences varying amounts of stretch during the forming process, the thinning of the part is more significant at the locations where contact the mold last, for example, corners or edges for a simple box. The effect can be compromised by zone-heating, (deLorenzi H.G, 1991) where localized temperature variations are intentionally applied instead of uniform heating. But it faces many problems when comes to practice. First of all, assuming there is a reliable database of material properties with respect to temperature changes at these elevated levels, getting the desired initial temperature map to obtain the desired thickness distribution at the end still requires either a trial-error procedure or a reliable solution of a series of nonlinear finite element iterations (Nied H.F, 1990). Moreover, even with such information in hand, how to obtain the desired temperature map is an additional issue and requires either another trial-error procedure or a numerical thermal analysis based on the heater settings (Bourgin P, 1995). Most of the time, small changes in temperature result in great changes in the mechanical behavior of the rubbery polymer and process parameters need to be continuously updated as the environmental conditions continuously changes. Therefore, even if a very careful numerical and experimental analysis is performed beforehand, the nature of the process requires close tracking for the best results (Bekisli, 2010).

An innovative way to stabilize the thermoforming process and acquire control is using knitted fabrics. As discussed previously, the deformation property of knitted fabrics is unique in two aspects; a) they are generally very easy to stretch and can be well-suited even for deep-draw forming applications, and b) they exhibit a sudden stiffening behavior at given biaxial stretch that is controllable via manipulate the knitting density. The concept is very simple: instead of struggling to control the polymer, knitted fabric can be introduced to control the deformation by geometric design.

In Bekisli's study, the finite element simulation of thermoforming using knitted fabric reinforcements was developed and further applied on controlling thickness distribution for long channel-like part. The numerical models will be described first and then the experiments to validate the models will be presented next.

Thermoformed long channels with a U-shape cross section are frequently encountered in the automotive industry. The advantage of this geometry in the numerical case is due to the fact that the length of the part is large compared to other dimensions, and a plane strain assumption can be combined with plain stress in the thickness direction. Therefore, the problem actually reduces to 1-D. and utilizing the symmetry condition along the width direction, only half of the strip will be meshed with proper symmetric boundary conditions on symmetry edge.

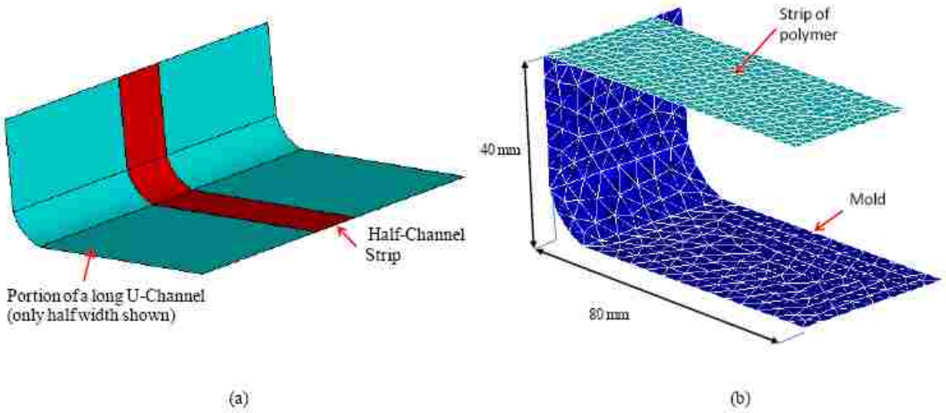
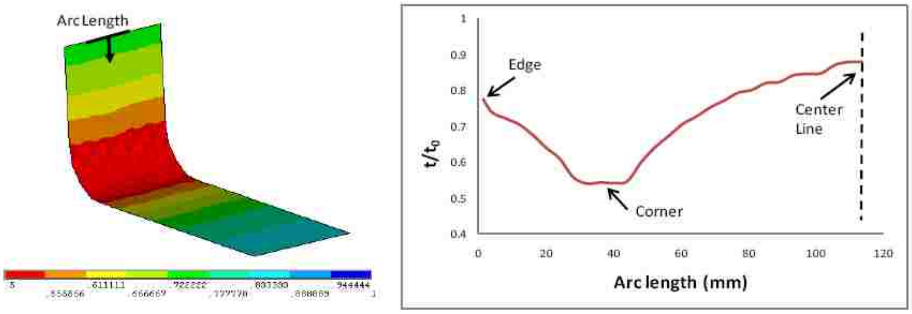


Figure 21 (a) a portion of long U-shape channel and the strip being considered, (b) FE mesh and mold geometry used in analysis

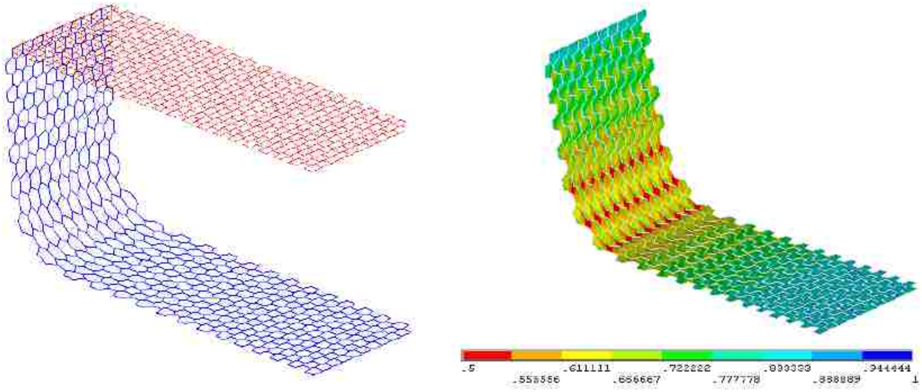
The finite element analysis predicts the thickness distribution plotted for Polypheneylene Oxide (PPO), uniformly at 168 ℃. The thickness values along a path starts at the edge as shown in Figure 22 (a) and passing along the width of the strip is presented in Figure 22 (b). Thickness in both plots is normalized with the original thickness of the sheet. As expected, the region corresponding to the corner stretches more than anywhere else and ends up with the most reduced thickness.



(a) (b)

Figure 22 Predicted thickness distribution after thermoforming of PPO strip at 168°C, (a) thickness contour plot, (b) thickness value along arc-length showing in (a)

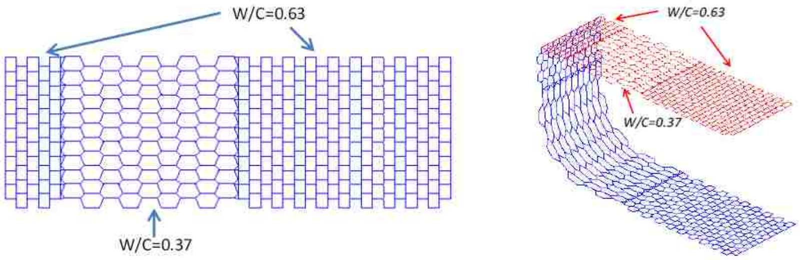
Next, suppose that the fabric is reinforced with an embedded glassfiber-knitted fabrics with the following pattern; Wale = 2.58 loops/cm, Course = 4.09 loops/cm (W/C = 0.63). Thermoforming simulation of the composite results in an improved distribution around the critical corner due to the fact that the fabric stiffens up at 70% stretch and distributes the further stretch to the neighboring regions. Simulation shows a better thickness distribution could obtain.



(a) (b)

Figure 23 Results of thermoformed PPO strip reinforced with uniform knitted fabrics; (a) Deformed and undeformed configuration of reinforcements, (b) Thickness distribution of the formed part.

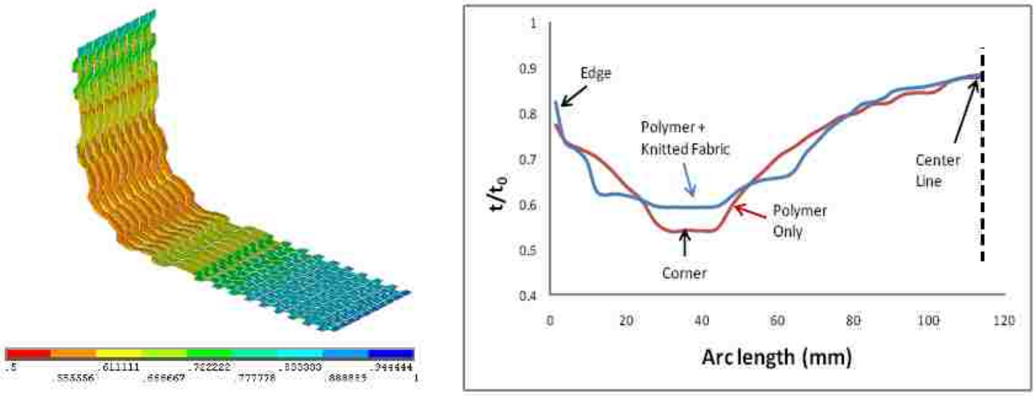
The thickness distribution can be further improved by tailoring the knitting pattern. This can be achieved by making the critical regions of the initial sheet stiffer than other regions, similar to zone heating principle. In other words, the knitting pattern can be so arranged that a pattern which stiffens up very early is placed at the critical regions before forming. In this case, a three-pattern arrangement is studied and shown in Figure 24; a knitted pattern of W/C = 0.37 in regions corresponding to corners and W/C = 0.63 elsewhere on the strip. The Figure 24 (a) is to emphasize the changing of knitting density. But the real knitting density will be tighten in the middle, opposite to what is showing in the Figure 24 (b).



(a) (b)

Figure 24 Three-pattern knit fabric hexagonal structure; (a) undeformed view, (b) deformed view.

When the forming is analyzed numerically, knitted fabric deformation is shown in Figure 25 (a) and the thickness distribution is shown in Figure 25 (b). As clearly seen, the distribution becomes more uniform, since after a stretch of 44%, the middle region becomes difficult to stretch further and pulls the neighboring regions that are still very deformable, thus distributing the total stretch to a larger section. (Bekisli, 2010)



(a) (b)

Figure 25 Results of thermoformed PPO strip reinforced with a “tailored” knitted fabric; (a) Contour plot, (b) Thickness distribution along the arc length and comparison with the polymer-only case.

In terms of experimental approach, the same order was followed.

The pure polymer sheet was sent into thermoforming machine first. Because of the nature of this elastomer and lacking support in the center of the sheet, it began to sag very fast. The pure sheet was forced to pull out before reaching its melting point. Saggy means stretch which makes the surface area much larger than before when the heating cycle ends. Then the same before-mentioned U-shape molds were used to mimic the long channel forming. The larger yet thinner sheet overlapped each other when touching the mold surface therefore wrinkles appeared. The Figure 26 shows clearly how it failed.

Figure 26 Forming failure on pure elastomer

In another attempt, the heating cycle was intentionally reduced to avoid saggy. Lack of heating time leaded to lower forming temperature. Under this case, the sheet conducted a stubborn performance. In other words, the sheet shrank significantly in the center forming area. That made the sheet an oval like shape in depth direction.

So based on those tests, conclusion can be drew that this elastomeric sheet could not form to other shape by itself. That made it inevitable to work with reinforcement.

With knitted fabric reinforcement, the result was much better. First of all, the composite was able to form and no significant shrinkage observed. And an obvious improvement should be mentioned during the heating process is that the composite only had limited sagging. Within knitted fabric reinforced, the distance of sagging was about half inch which is normal case in thermoforming process. The inner square marked in blue was the U-shape area before forming. Inside the square, simple 1” by 1” grid was marked as well. The Figure 27 clearly shows what specimen looked like after thermoforming. The curvature in blue also implied some basic theory of thermoforming which is the deformation is non-uniform as well as the thickness distribution.

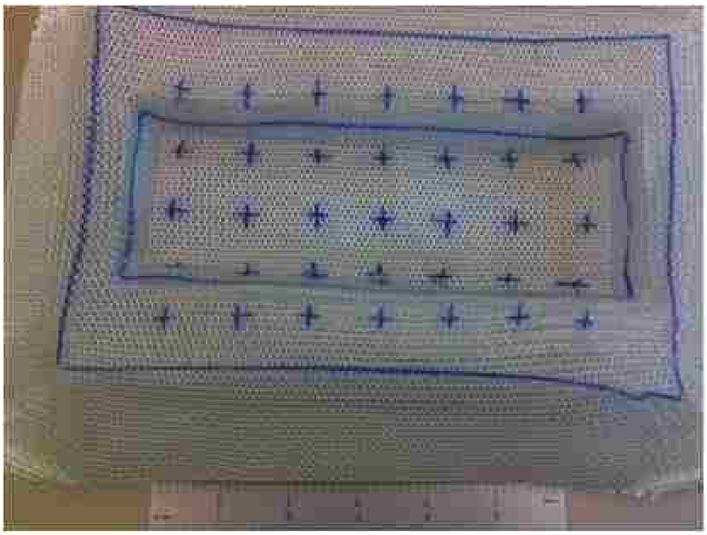


Figure 27 Formed composite

To close up the side wall and corner, there is slight difference in loop density between side wall fabric and bottom fabric. The straight line in red is for better distinguishment. It seems loop distance in wale direction of side wall is larger than bottom. To confirm and quantify this enlargement, careful measurement was done by micrometer. Table 4 gives a glance of the outcomes.

Figure 28 Close up critical area

Table 4 Loop distance in wale direction

	Side wall	Bottom
Before forming	0.1 inch	0.1 inch
After forming	0.12 inch	0.1 inch

The measurement was done in various spots to minimize error. It indicates that the loop elongation in wale direction is about 20% in the critical area, i.e. the side wall.

One more detail should be mentioned is that in the forming phase, the vacuum was applied before the male mold closing. That can help minimize the thickness variation caused by mold contact. But the following side effect is that the surface of final specimen is not smooth in certain area. The matrix material was suck out from each fabric loop by strong vacuum force and formed a hilly-like surface. Fortunately, this hilly area only takes about 30% of entire specimen. So the thickness distribution still can be measured and was dealt deliberately. For showing the data more directly, the cross section of the specimen was drawn in Figure 29. As usual, multiple spots were taken for minimum error.

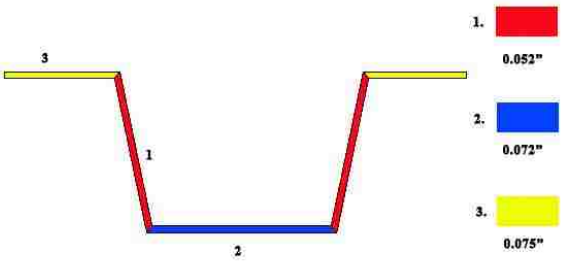


Figure 29 Thickness distribution on experimental specimen

Compare to original sheet thickness 0.089", the three areas in Figure 29 were all stretched thinner during the forming phase. And as predicted in numerical study, the side wall is about 30% thinner than others. This experimental approach is definitely a strong support of the simulative works.

5.4. Current and potential applications

Fiber reinforced composite are widely used in all kinds of products to get better mechanical performances. Differ from woven fabric, the knitted fabric reinforce composite should apply on energy absorbing for better utilize its flexible property, as mentioned in previous chapters.

With outstanding flexibility, impact absorption could be its main application. Currently yet how the composite will behavior under low speed impact is unknown, but my peer J. Payne is working on it and I believe very promising results is coming soon. If it applies well under low speed impact, high speed impact will proceed in the future. That sure can open many markets from personal security to even military applications. Here in the Figure 30 shows some examples where knitted fabric reinforced composite can be used.

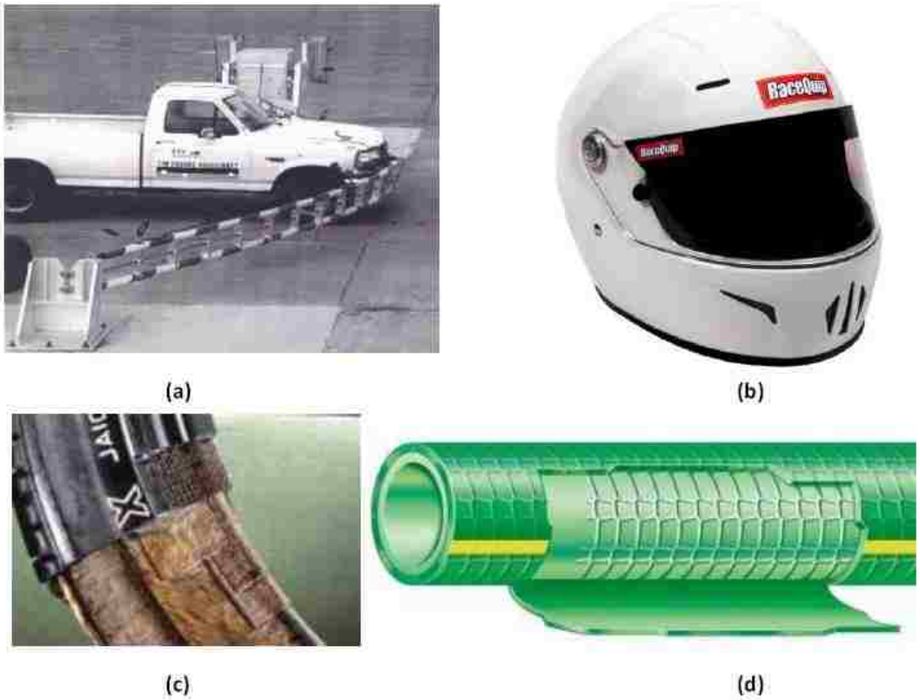


Figure 30 Some current and potential uses of flexible composites: (a) Crash cushion and barrier applications, (b) Protective wear, (c) Tires reinforced with knitted fabric, (d) Lightweight, high strength and flexible hose and pipe applications.

Figure 30 also implies automotive industry might be the largest potential market. Plastics have been commonly used in exterior and interior panels such as front or rear bumpers, claddings, and rocker panels. To enhance their impact absorption ability in order to protect people, knitted fabric reinforcement could be introduced. Moreover, since thermoforming is one of the key manufacturing processes in this industry, knitted fabric reinforcement can play a crucial role during the manufacturing as well.

6. Conclusions and future prospects

6.1. Conclusions

The deformation behavior of composite made of knitted fabric reinforcement and elastomer matrix was studied. The analysis showed better utilization of knitted fabrics will be the matrix material should be at least as flexible as the fabric itself. Elastomers were investigated in this regard instead of more common thermoset or thermoplastic materials. Uniaxial tension test showed this composite can achieve elongation over a few hundred percent which is quite promising for energy absorbing applications. Knitted fabric is embedded in the elastomer matrix which might yield fabrics from further elongation.

Some experiments were done to validate the numerical models established in previous study. The innovative idea on thermoforming process was not only simulated, but also validated in experiments. Thermoforming with embedded fabric was introduced as well. With the use of these models and specimens, it was shown that some common problems can be slightly reduced or completely eliminated. By an intentionally designed knitting pattern, the thickness distribution of final product was shown to be significantly improved. This was approached by placing knitting pattern with less stretchability under the critical regions like the corner or side walls. By doing that, extra support to critical regions was obtained.

Another problem can be challenged by reinforced with knitted fabrics is the high sensitivity of thermoforming process to the small changes in processing conditions, especially to thermal variations. This is caused by the drastic transition of mechanical properties of the polymer at thermoforming temperature range. Since the mechanical properties of the knitted fabrics will not be affected by thermal variations and its stiffness is larger than molten polymer, deformation of the composite can be stabilized.

6.2. Future prospects

Plain weft knitting was modeled to start with due to it is the simplest. Other knitting patterns, such as rib-knit and warp-knit can also worth further exploration. Study of new knit patterns can be the first natural extension of this study.

Material variations can provide numerous topics to investigate as well. Only E-glass fiber and PEBAX was test in this study. With various properties, other materials like carbon fiber, Kevlar, polyester, and other thermoplastic elastomers can be used too. The big picture is to establish a database for deformation behaviors and other properties in different combinations of these potential materials. Then when come to applications, people can easily get information and references from the database. Considering there are so many potential materials can be used in this manner, the data collection could take years of efforts.

Besides making the composite by embedding the reinforcement into the matrix material, there is another way to arrange two materials into a composite which is sandwich formation. To be more specific, that means when these layers are combined, the skin layers should be attached to each other only at edges and at limited number of other locations if needed. The key idea is to free the fabric to achieve larger deformation than embedment. There are some methods to manufacture this kind of composite, such as, sewing the edges or compression molding the edges. Twin-sheet thermoforming is also a very interesting process to produce hollow composite with knitted fabrics in the middle. The Figure 31 shows the idea of manufacturing a twin-sheet composite. And if the part is large in size, it might require that skin can attach more locations to assure structural stiffness. This can easily be solved by simply adding tack-offs on the mold.

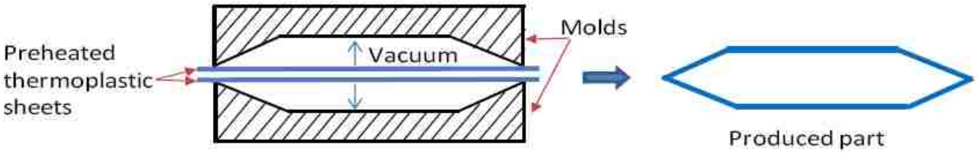


Figure 31 Simple twin-sheet thermoforming to form hollow shaped parts

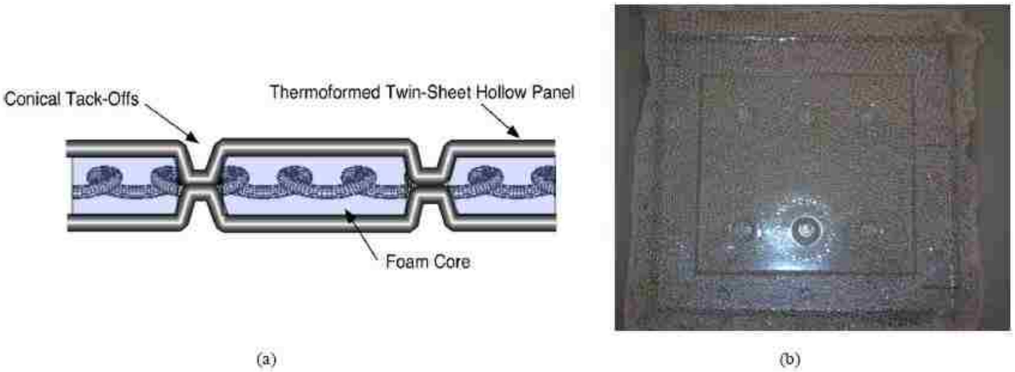
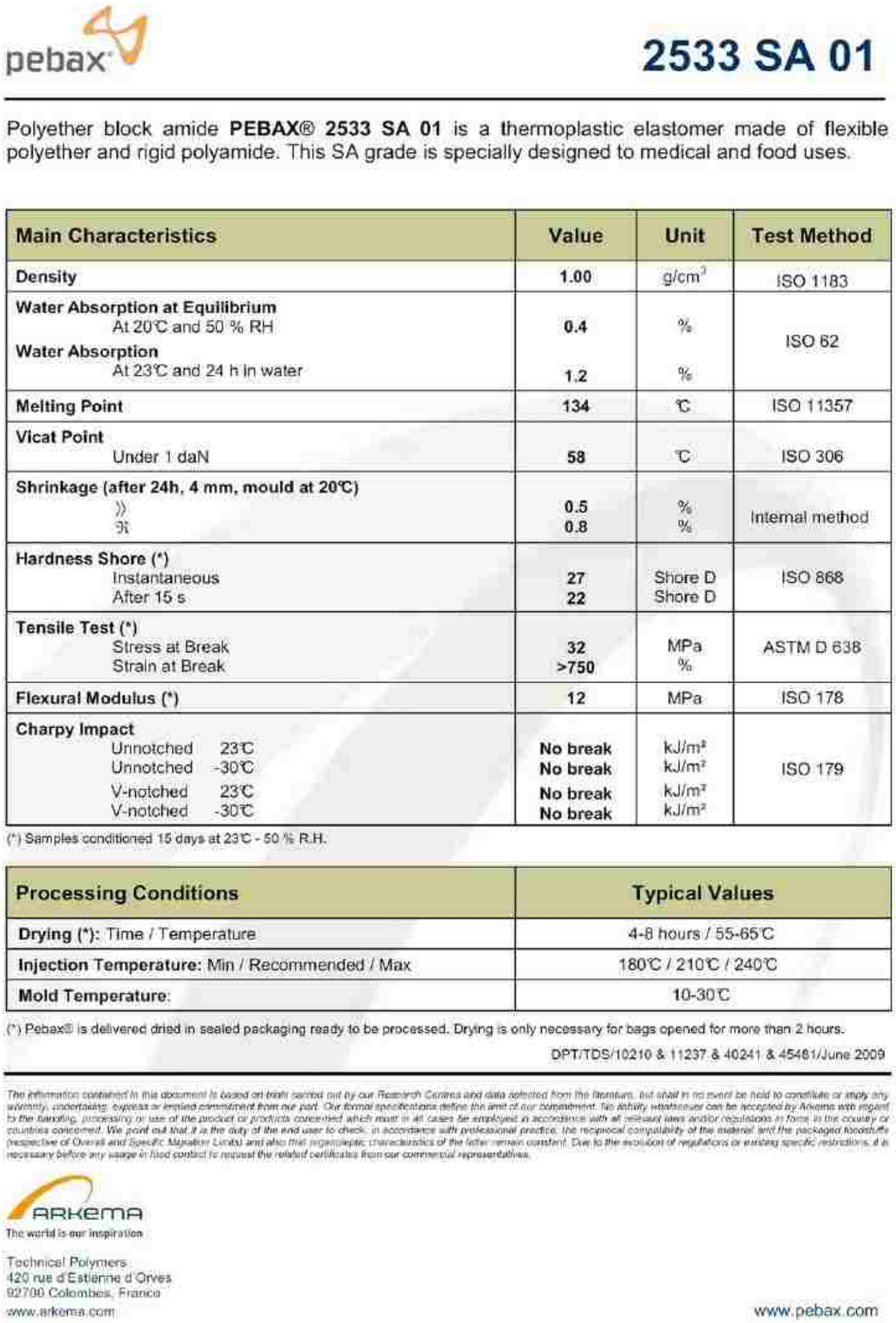


Figure 32 (a) Illustration of a flexible composite sandwich that can be produced by twin-sheet thermoforming; (b) A part produced with polystyrene skins and glassfiber fabric, pictured without the foam core. Tack-offs are designed to provide additional shear resistance

The picture of Figure 32 (b) is done by Cai who did very good job on similar topic in Lehigh University. He explored the methods of making twin-sheet composite. It is worth to mention that the matrix material he used is Polystyrene instead of thermoplastic elastomers. His work focused on manufacturing, no further test on mechanical properties was dealt. So twin-sheet with knitted fabric reinforcement can be another possible direction to go.

Appendix I PEBAX



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Main Characteristics	Value	Unit	Test Method
Density	1.00	g/cm^3	ISO 1183
Water Absorption at Equilibrium At 20℃ and 50 % RH **Water Absorption** At 23℃ and 24 h in water	0.4 1.2	% %	ISO 62
Melting Point	134	℃	ISO 11357
Vicat Point Under 1 daN	58	℃	ISO 306
Shrinkage (after 24h, 4 mm, mould at 20℃) 》 ℜ	0.5 0.8	% %	Internal method
Hardness Shore (*) Instantaneous After 15 s	27 22	Shore D Shore D	ISO 868
Tensile Test (*) Stress at Break Strain at Break	32 >750	MPa %	ASTM D 638
Flexural Modulus (*)	12	MPa	ISO 178
Charpy Impact Unnotched 23℃ Unnotched -30℃ V-notched 23℃ V-notched -30℃	No break No break No break No break	kJ/m^2 kJ/m^2 kJ/m^2 kJ/m^2	ISO 179

(*) Samples conditioned 15 days at 23℃ - 50 % R.H.

Processing Conditions	Typical Values
Drying (*): Time / Temperature	4-8 hours / 55-65℃
Injection Temperature: Min / Recommended / Max	180℃ / 210℃ / 240℃
Mold Temperature:	10-30℃

(*) Pebax® is delivered dried in sealed packaging ready to be processed. Drying is only necessary for bags opened for more than 2 hours.

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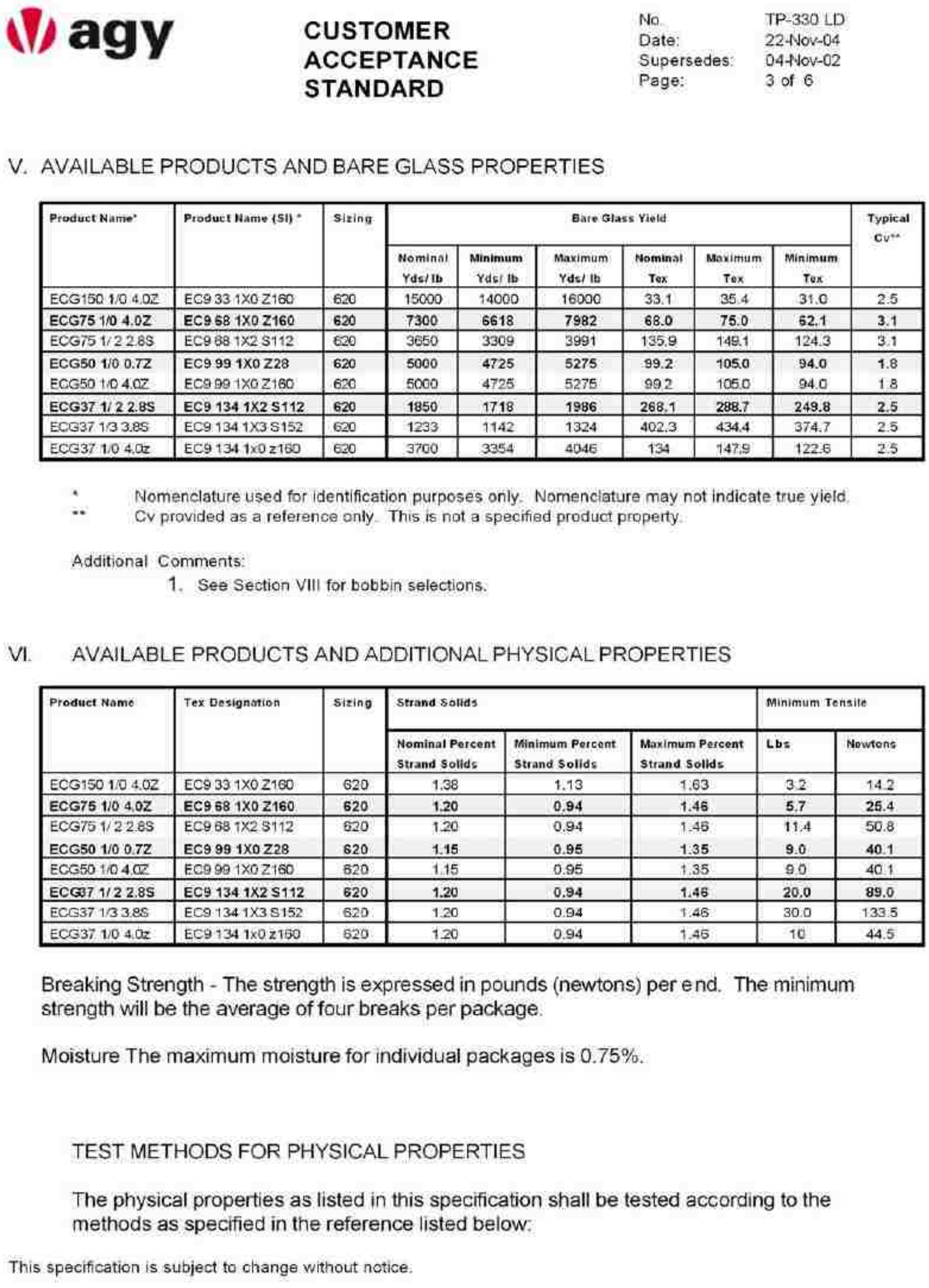
Appendix II Glass Fiber



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CUSTOMER
ACCEPTANCE
STANDARD

No.	TP-330 LD
Date:	22-Nov-04
Supersedes:	04-Nov-02
Page:	3 of 6

V. AVAILABLE PRODUCTS AND BARE GLASS PROPERTIES

Product Name*	Product Name (SI) *	Sizing	Bare Glass Yield						Typical Cv**
			Nominal Yds/ lb	Minimum Yds/ lb	Maximum Yds/ lb	Nominal Tex	Maximum Tex	Minimum Tex	
ECG150 1/0 4.0Z	EC9 33 1X0 Z160	620	15000	14000	16000	33.1	35.4	31.0	2.5
ECG75 1/0 4.0Z	**EC9 68 1X0 Z160**	**620**	**7300**	**6618**	**7982**	**68.0**	**75.0**	**62.1**	**3.1**
ECG75 1/ 2 2.8S	EC9 68 1X2 S112	620	3650	3309	3991	135.9	149.1	124.3	3.1
ECG50 1/0 0.7Z	**EC9 99 1X0 Z28**	**620**	**5000**	**4725**	**5275**	**99.2**	**105.0**	**94.0**	**1.8**
ECG50 1/0 4.0Z	EC9 99 1X0 Z160	620	5000	4725	5275	99.2	105.0	94.0	1.8
ECG37 1/ 2 2.8S	**EC9 134 1X2 S112**	**620**	**1850**	**1718**	**1986**	**268.1**	**288.7**	**249.8**	**2.5**
ECG37 1/3 3.8S	EC9 134 1X3 S152	620	1233	1142	1324	402.3	434.4	374.7	2.5
ECG37 1/0 4.0z	EC9 134 1x0 z160	620	3700	3354	4046	134	147.9	122.6	2.5

* Nomenclature used for identification purposes only. Nomenclature may not indicate true yield.
** Cv provided as a reference only. This is not a specified product property.

Additional Comments:

1. See Section VIII for bobbin selections.

VI. AVAILABLE PRODUCTS AND ADDITIONAL PHYSICAL PROPERTIES

Product Name	Tex Designation	Sizing	Strand Solids			Minimum Tensile	
			Nominal Percent Strand Solids	Minimum Percent Strand Solids	Maximum Percent Strand Solids	Lbs	Newtons
ECG150 1/0 4.0Z	EC9 33 1X0 Z160	620	1.38	1.13	1.63	3.2	14.2
ECG75 1/0 4.0Z	**EC9 68 1X0 Z160**	**620**	**1.20**	**0.94**	**1.46**	**5.7**	**25.4**
ECG75 1/ 2 2.8S	EC9 68 1X2 S112	620	1.20	0.94	1.46	11.4	50.8
ECG50 1/0 0.7Z	**EC9 99 1X0 Z28**	**620**	**1.15**	**0.95**	**1.35**	**9.0**	**40.1**
ECG50 1/0 4.0Z	EC9 99 1X0 Z160	620	1.15	0.95	1.35	9.0	40.1
ECG37 1/ 2 2.8S	**EC9 134 1X2 S112**	**620**	**1.20**	**0.94**	**1.46**	**20.0**	**89.0**
ECG37 1/3 3.8S	EC9 134 1X3 S152	620	1.20	0.94	1.46	30.0	133.5
ECG37 1/0 4.0z	EC9 134 1x0 z160	620	1.20	0.94	1.46	10	44.5

Breaking Strength - The strength is expressed in pounds (newtons) per end. The minimum strength will be the average of four breaks per package.

Moisture The maximum moisture for individual packages is 0.75%.

TEST METHODS FOR PHYSICAL PROPERTIES

The physical properties as listed in this specification shall be tested according to the methods as specified in the reference listed below:

This specification is subject to change without notice.

1. Yards per Pound (Linear Density - TEX) - W-07Ea-T*
2. Ignition Loss - W-07Ea-T*
3. Breaking Strength - S-01Gd*
4. Twist per Inch (per Meter) - D-15A-T*.

* Owens Corning Test Methods. Copies available upon request.

Additional Comments:

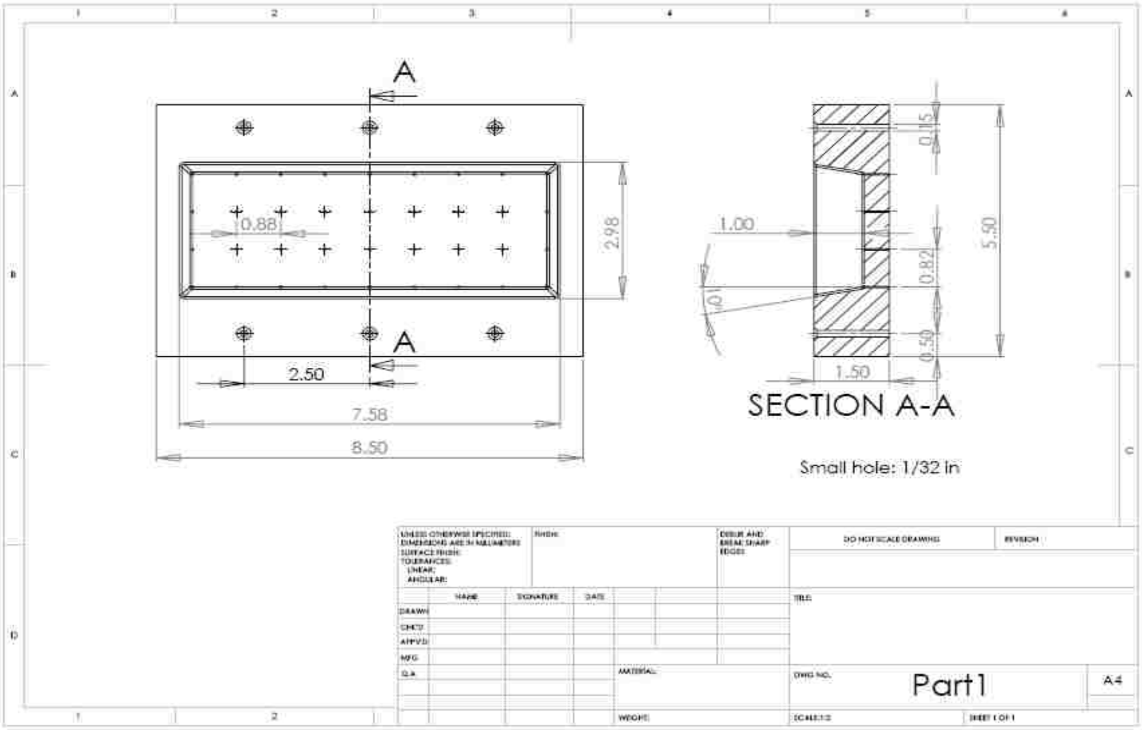
1. Physical test methods will soon be changed to ASTM Methods where applicable.

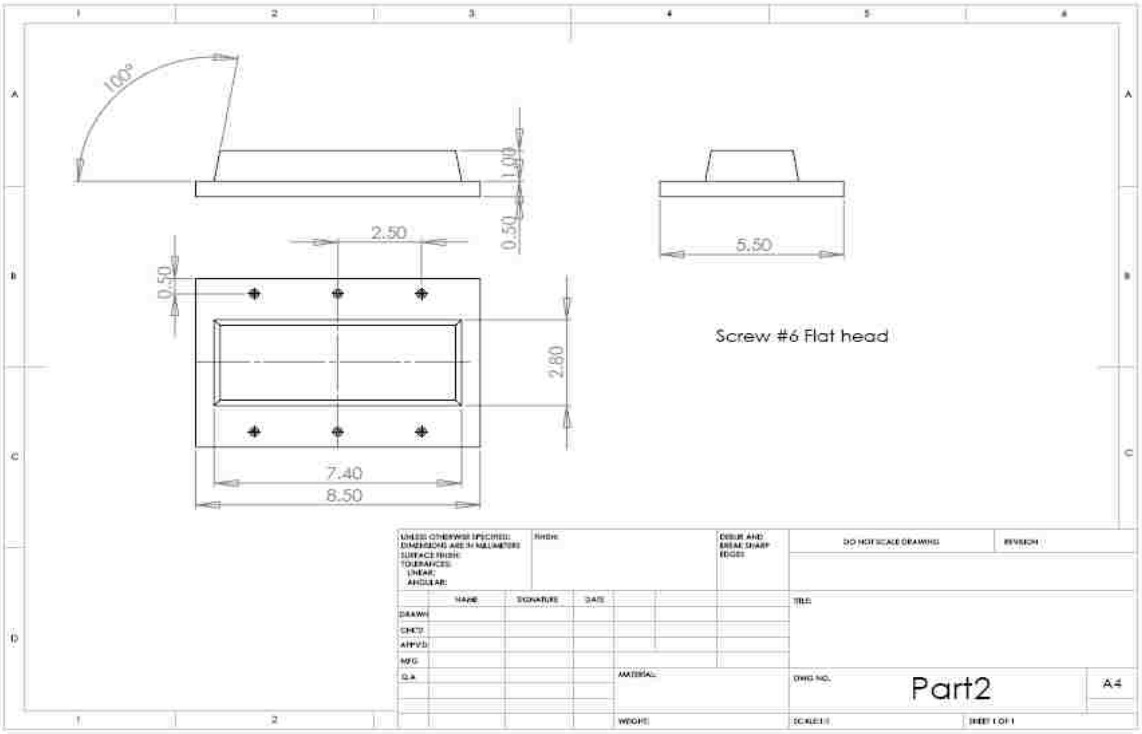
VII. AVAILABLE PRODUCTS AND VISUAL PROPERTIES

Product Name	Tex Designation	Sizing	Maximum Average Broken Filaments (360° Count)	Filament Count*	Approximate Yarn Diameter		Twist Tolerance	
					Inches	mm	TPI	TPM
ECG150 1/0 4.0Z	EC9 33 1X0 Z160	620	30	204	0.0080	0.203	± 0.60	± 24
ECG75 1/0 4.0Z	**EC9 68 1X0 Z160**	**620**	**30**	**408**	**0.0106**	**0.269**	**± 0.60**	**± 24**
ECG75 1/ 2 2.8S	EC9 68 1X2 S112	620	30	816	0.0149	0.378	± 0.57	± 23
ECG50 1/0 0.7Z	**EC9 99 1X0 Z28**	**620**	**30**	**612**	**0.0140**	**0.356**	**± 0.21**	**± 8**
ECG50 1/0 4.0Z	EC9 99 1X0 Z160	620	30	612	0.0140	0.356	± 0.60	± 24
ECG37 1/ 2 2.8S	**EC9 134 1X2 S112**	**620**	**30**	**1632**	**0.0224**	**0.568**	**± 0.57**	**± 23**
ECG37 1/3 3.8S	EC9 134 1X3 S152	620	30	2498	0.0261	0.663	± 0.57	± 23
ECG37 1/0 4.0z	EC9 134 1x0 z160	620	30	816	0.0156	0.396	± 0.60	± 24

* The number of filaments and approximate yarn diameter are for reference purposes only. Yarns are controlled according to yards per pound (linear density-TEX)

Appendix III Mold Drawings





Appendix IV Compression Molding User Manual

Major features:

- Platen size: 14” square
- Maximum force: 24 tons
- Maximum temperature: 600 ℉
- Thermal uniformity: ±5 ℉
- Heating rate: 15 ℉ per minute
- Cooling rate: 50 ℉ per minute

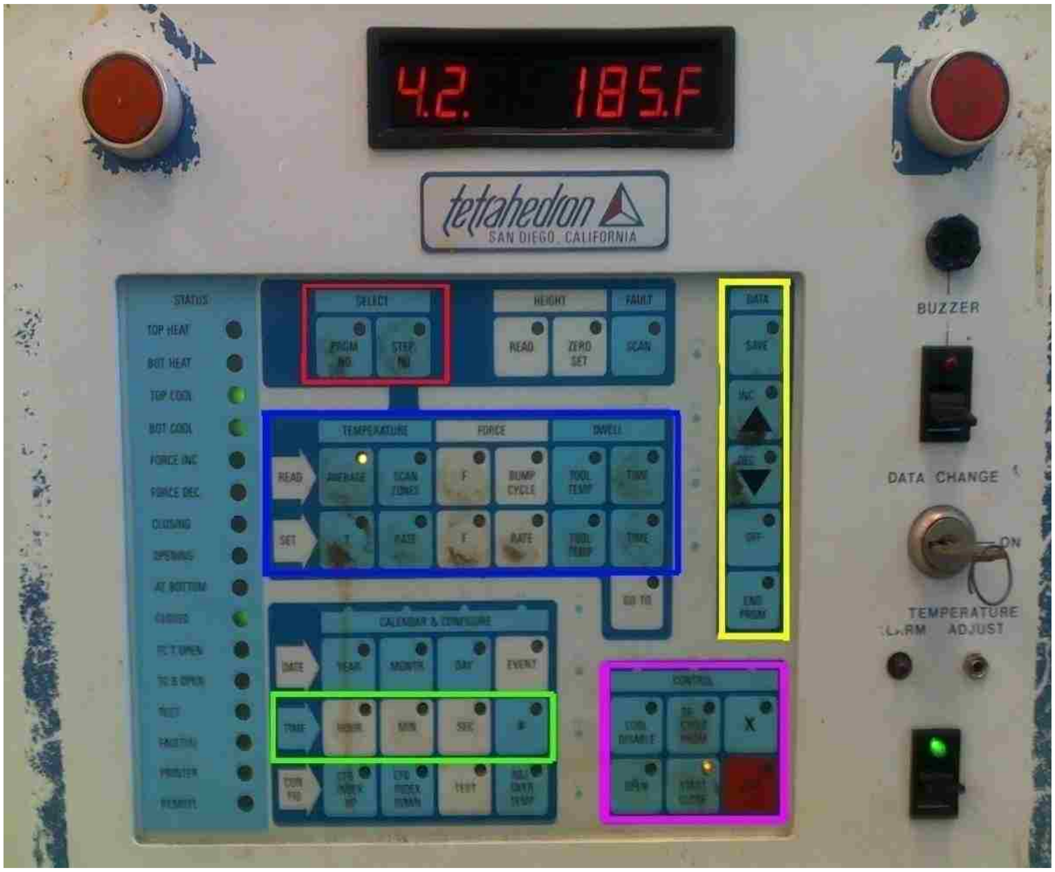
Zoom in to the control panel, there are five sections that are often used and distingushed by red, blue, yellow, green, and purple for better reference. Each sections will be introduced.

Basic layout:

The black switch on the right bottom is the power switch.

The two red button on the top is platen closing button. Need to be push simutanously to close the platen.

The screen on the top center shows three things, 1) program number (‘4’ in the picture), 2) step number (‘2’ in the picture), and 3) the parameter you are reading or setting (‘185°F’ in the picture).



Red section:

This section is for program number and step number selection. There are six available programs to choose. Each program could have up to eight steps. Then choose the step number. Take the picture for instance, the machine is working on program number 4, step number 2.

Yellow section:

This section is for control the data by increasing or decreasing. Any number changing is done by this section.

Blue section:

This section is for parameter reading and setting. The top row is for reading current average temperature, force, and time. It is very useful during the compression process. On the other hand, bottom row is for setting parameters which need to be done before close the platens. This is the most important section.

Green section:

This is very useful when you trying to set up time. If you want to have a 12 hours cycle, changing in second will be ridiculers. This section allows you to change in hour, minute, or second. Other than that it will not be used.

Purple section:

This section is for control, such as start or emergency stop.

Example:

After set up the material and mold properly in the platen, you can start pressing ‘program number’. Then press ‘increase’ or ‘decrease’ to adjust the number to desired. Then press ‘step number’ to step 1. Now you can input the desired parameter. Take heating time for example, press ‘time’ in setting row, blue section. Then press ‘increase’ or ‘decrease’ to adjust the time. Finally press ‘save’ in yellow section. The dwell time is set up. Heating temperature, pressing force follow the same rule. When step 1 is finished, press ‘step number’ again to enter next step, follow the same rule. If want the next step be the end, just press ‘end’ in yellow section. Finally ‘save’ all data, change ‘step number’ to 1. Press ‘start close’ in purple section, there will be multiple lights flashing. Press red button together to send the platen closing. Then after certain time, the platen will open automatically and you can remove the mold and material.

Notice:

During the process, you can press read row of blue section, but do not change ‘program number’ or ‘step number’. That will interrupt current program or step.

Dwell time is not required during preheat or cooling cycles.

Do not use temperature rate higher than 250 ℉/min.

Remember to log equipment time in log book.

Appendix V Knitting Machine User Manual

In this instruction, the common steps and some important notice will be given in picture and description for better understanding. If you follow the rules and steps, you will be able to knit a fabric in short time. The crucial part of this knitting machine is the needles. So the first rule is do not break or bend the needles. They are fragile under force and very painful when come to replacement. But worst-case scenario, the needle replacement, will be shown in the very end of this manual.

Another personal feeling I think should be said in the beginning is that the machine is very tricky to use. Every point I emphasized later can play a role in your failure if not being careful. It took hours for me to finally figure out a system for success knitting. Now the machine is sitting there and ready to work, but it might be moving to another lab in future therefore need to be set up again. So I think creating the manual from the beginning is the best way to pass the knowledge without losing anything.

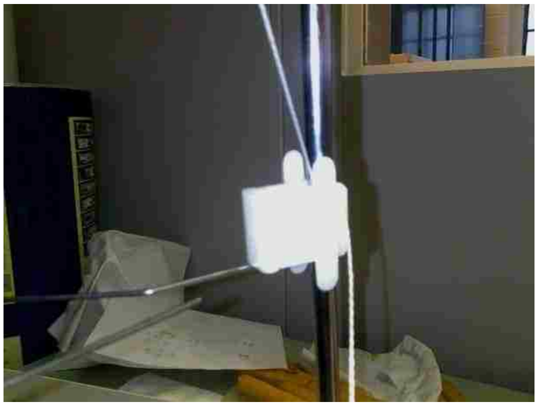
To start with, the proper fiber feeding system should be set up. In the left hand side of the machine, there is a small hole allowing the fiber feed in from the spool.

Then the fiber should go into the triangle guider on the erect bracket. The white plastic holding it has another function that allows tying the fiber when not using.

The fiber goes to the white knob. That controls the friction of the fiber therefore control the tightness of fiber when knitting. There are 10 levels. 1 means minimum friction, 10 means maximum. The selection of proper friction depends on fiber material. For this glass fiber that currently used, minimum friction is the best. There is a V-notch indicating which level it is.

Then the fiber connects the antenna-like spring. When knitting, the spring will go up and down to assure proper fiber tension. The criterion of good friction in white knob is the spring will not bend all the way down and hit the next part.

The next part is another guider. The fiber needs to go through the circle. After that, the fiber can be tied to the white plastic holder and the set up for fiber is done.



Handle, the main part of this machine needs to be introduced. It consist two parts, the white plastic one on the top, and the shiny steel part on the bottom. They connect by two white plastic knobs that can be unlocked. When knitting, the fiber can go wrong therefore stuck the handle. The only way to free the handle is to remove the steel part and untie all the fibers. The density control knob pointed out in red controls the knitting distance in wale direction. Since the course direction is fixed, it further controls the knitting density. There are multiple levels options. The smaller number means higher density. For this material, under level 2 cannot achieve because the tighter it goes, the easier fiber breaks. And above level 6 is good starter for a new sheet. The switch pointed out in blue is a pattern selector. It offers multiple knitting patterns. But for plain-weft knitting, it should be positioned like the picture.

Back to knit a sheet. The next step is set up the needles. Select proper length of needles firstly. Due to the knitted fabric curl a lot, make sure to use more needles than the actual fabric length you want. Pull the selected needles all the way out. Then slide the handle over them from right to left and come back to right again. I will name it ‘slide a cycle’ for better understanding. Then the selected needles will become shown in picture, about half inch closer to you.

Then what you need to do is pull every other needle all the way out like the second picture. The needle set up is done.

To here, all the set up is done. Now come to the knitting. Let the fiber follow the path as shown in picture. Through center hole of the steel, go underneath the steel, and lay above the needles. Left hand should stretch a little to keep fiber straight.

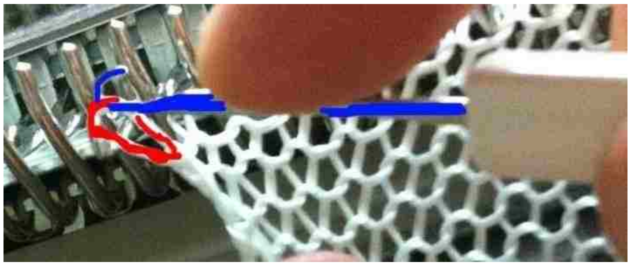
Then use right hand proceed slide cycle several times. After succeed in first couple of rows, the two weights should be used to stretch the fabric, preventing curl to mess with later knitting.

Even using these two weights helping out, there is a gap in the middle need to be stretched by your left hand if the sheet length is like the picture. So I found another way to stretch that is using cardboard and push pins.

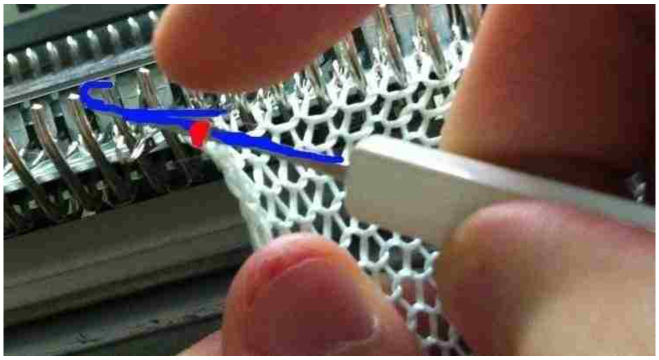
After nailed the fabric on the cardboard, the left hand can be focused on left and right ends of the sheet, because those are the easiest curling locations. So the left hand should stretch the sheet when right hand is knitting. Keep knitting with both hands until you have desired length of fabric sheet.

When finished, you need to make knot to every loop manually using certain tool. I named that tool ‘needle pen’ for better understanding.

It is the same needle used in the machine. It consists of two parts, hook and latch. The right finger should control the latch when making knot. When starting, place the handle in the very right first. And then use the needle pen to hook the first left loop, left hand hold the sheet still.



Then slide right hand forward to make the fiber loop under the latch.



Keeping pressure on the latch, the front hook goes to the next fiber loop.

Then close the latch, slide the needle pen backward to finish one knot.

Repeat the same movement to each loop. Proceed with caution, especially right hand. Because if you lose it, the entire sheet will be tore apart and all efforts will turn into trash. In the right end, the chance of failure raises. So I will highlight this part.

When come to the last loop, stretch more like the picture did. Then hold the loop with your left finger. Then use the notch pointed in red circle to cut the fiber. And finally make a knot using the circle and rest fiber.

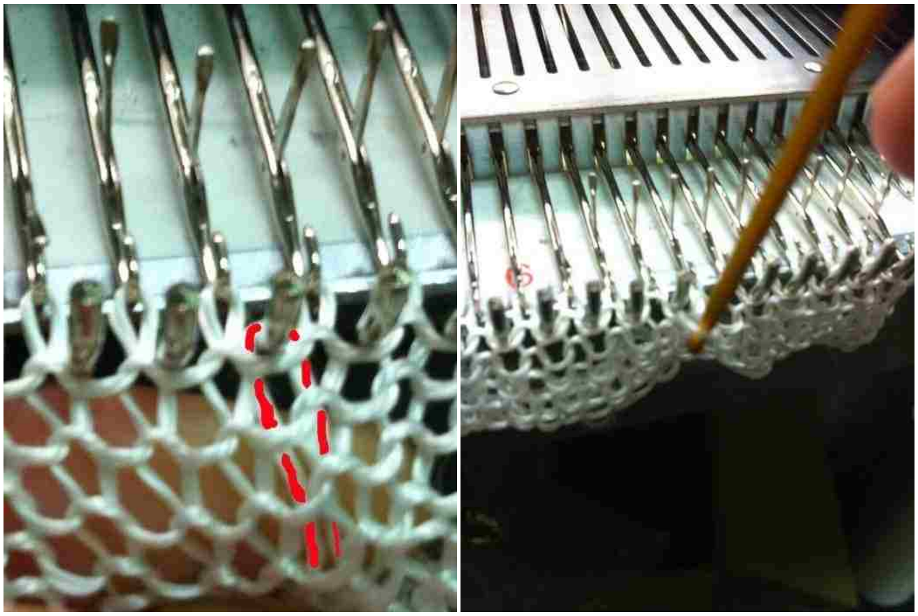
To here, a brand new sheet is done.

It may seem hard, but all you need to do is practice. When you can dexterous handle the needle pen, you are very close to knit large sheet in short time.

Troubleshooting

This section will generally include two parts, one is a small trick when knitting, another is how to disassemble the machine in needle replacement.

Firstly, when starts knitting a new sheet, the first couple of rows are the easiest place the fiber can go wrong. By go wrong it means missing loop. But if you keep knitting, any type of missing loop can convert to one and only type of flaw. That is the red in the picture.



The loop should not have any contact with the front cylinder like pin. It is very easy to fix with a yellow pen like tool in the picture. What you need to do is unhook it.

The worse case is the handle stuck by the fiber and cannot move. Like said before, do not force it, otherwise there is high possibility to bend or even break the needle. You should twist the two white knobs and remove the steel. Cut or remove the fiber and start over.

The worst case scenario is a needle break and need replacement. I will show a serious of picture here to give you a hint how complicated it is. Due to that was done a while ago and only once, I am not completely sure that is the best way to do it. But it worked after spent 4 hours disassembling and reassembling. So needle replacement is the last thing you want to do.

Firstly, remove the handle, unscrew and open the plastic lid on the left.

Then, do the same to right lid.

The main part can separate from the shell after remove more screws. But several L-shape steel connectors are still on the main part. Mark the positions and unscrew them.

The needles are locked by spring (blue arrow) and a U-shape track (red arrow).

Now you need to do is remove the U-shape track by unscrewing. Then the tension on the needles is gone therefore you can replace the bad one.

To here, we are half way done. Now it need to be reassembled. The only thing need to be highlighted is how to put the U-shape track back. Since there was spring tension on it when removing, it is not the samw way to put back. Now you need to do is pull all the needles out like to the right of the blue line.

Then slide the U-shape track in and tight all screws. And use tweezers to pull every single needle back and lay on top of the U-shape track. That can be very time consuming.

After finishing the needles, other works are just reversing what you did earlier. Then the needle replacement is finished.

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VITA

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This thesis is typed by the author.