# Methods for Increasing the Thermal Conductivity of Ultra-High Molecular Weight Polyethylene (UHMWPE)

by

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## ABSTRACT

A two-part study was conducted to determine methods for producing ultra-high molecular weight polyethylene with high thermal conductivity by way of polymer chain orientation. The first portion of this report surveys current research involving polyethylene chain orientation and manufacturing. This section includes analysis of shish-kebab morphology, past polymer thermal studies, self-reinforcement studies, manufacturing techniques, and experimental techniques for low thermal conductivity materials.

The second portion reviews the results of an experiment conducted to test the feasibility of stretched thermoforming of UHMW-polyethylene. Sheets of UHMWPE were stretched and tested for anisotropy in thermal conductivity. For samples with draw ratios of $\lambda \approx 10$, anisotropy in thermal conductivity was observed to increase. These results show potential for future development of this proposed methodology.

Thesis Supervisor: Gang Chen
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# 1. Introduction

Ultra-high molecular weight polyethylene has been shown in past studies to exhibit increased thermal conductivity as its polymer chain orientation increases. In these studies, chain orientation is achieved by various mechanical stretching techniques. However, methods for developing this technology have not been widely adopted, partly because of a lack of understanding of the mechanisms involved in the thermal property changes and partly because the manufacturing processes have not been fully developed. The first portion of this report will review past research regarding the relationship between polymer chain orientation, morphology, and thermal conductivity. The second portion will describe an experiment conducted to test a possible manufacturing approach for oriented UHMW-polyethylene.

## 1.1. General information regarding UHMWPE

Ultra-high molecular weight polyethylene, commonly referred to as UHMWPE, is a thermoplastic composed of very long polymer chains and characterized by strong mechanical properties. Amongst its many notable qualities are its high impact strength, high resistance to corrosion, high resistance to abrasion, and low coefficient of friction.

## 1.2. Applications

Because of these very advantageous characteristics of UHMWPE, it has been commercialized for many purposes. Ultra-high molecular weight polyethylene fibers have been developed into rope products such as Dyneema SK65[1] because they are have high strength to weight ratios and offer vibration damping under elongation (Govaert et al., 1993). These fibers are used in high strength applications ranging from bullet-proof vests to high

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[1] Dyneema SK65 is a registered product of DSM

strength ropes. (DSM) The low abrasion and low friction qualities of UHMWPE makes it a popular choice for industrial handling applications, and it has been the material of choice for hip and joint replacements since the 1970s (Wu et al., 2000).

## 1.3. Thermal Properties and Potential Demand

Despite the advantageous mechanical properties of UHMWPE, product design is limited by the low thermal conductivity of polyethylene. With typical thermal conductivity values ranging from 0.4 to 0.5 W/m K (Goodfellow), ultra-high molecular weight polyethylene is out of specifications for designs that require significant heat transfer. Such engineering applications could include electronic enclosures or small motor housings.

Furthermore, the concepts explored in this study for improving the thermal conductivity of polyethylene could potentially be applicable for other types of polymers. For this reason, engineers and researchers that utilize or study other plastics may benefit from an improved understanding of the thermal conductivity characteristics of UHMWPE.

# 2. State of Current Research

The widespread use of ultra-high molecular weight PE is due in part to the extensive research that has been conducted to better understand this polymer. In this section of the report, relevant past research will be reviewed and discussed. The section will begin by exploring the current theory of polymer chain structures to better understand micro- and nano-scale heat transfer mechanisms. It will then shift focus to thermal conductivity experiments, mechanical properties experiments, and methods for quantitative thermal conductivity testing.

## 2.1. Current theory on polymer chain structures

Research is being conducted to characterize the mechanisms of polymer orientation and morphology. One important component of this research is an induced morphology known as shish-kebab structure (Pornnimit and Ehrenstein, 1992). This paper will provide a summary of the current state of the shish-kebab research because this research field is both extensive and still in development.

It is well known that polymer chains, especially in high molecular weight polymers, exhibit entanglements and non-oriented structures in their unstretched state. When a force, often via a flow field, is used to stretch the polymer chains, they undergo a transition to the shish-kebab morphology by way of mechanisms that are not entirely clear to this day. A recent study theorized that the shish structure, which is shown in Figures 1 and 2 and appears as the shaft part of the polymer chain, is created when nearby chains that are aligned with the flow field stretch out and disentangle. These shish structures then act as nucleating sites for kebab structures which are also shown in Figures 1 and 2 and appear as radial disks. It is not clear exactly how kebab structures form, but some believe they form from coiled sections of the polymer chain. The Somani et al. (2005) study theorized that shish structures form between polymer chains before kebab structures form. They based this theory on the fact that after kebab structures were dissolved using nitric acid, scanning electron microscopy still showed interconnected shish structures. (Somani et al., 2005)

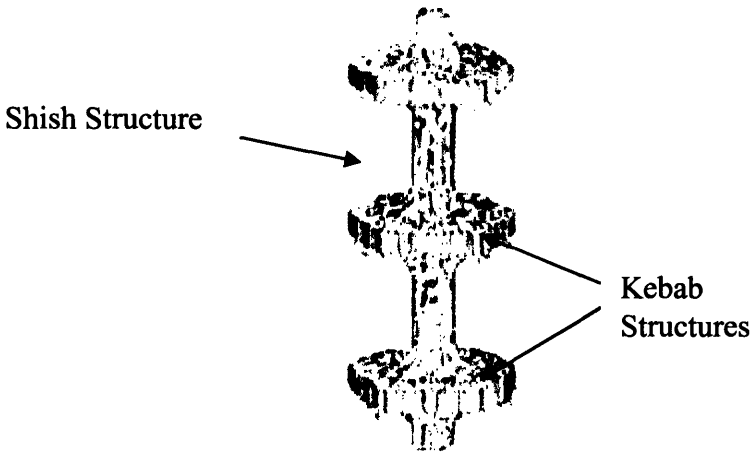

Figure 1: Schematic drawing of shish-kebab microstructure in polyethylene. (Adapted from Somani et al. (2005) originally from Processing of Polymers 18:189,1997)

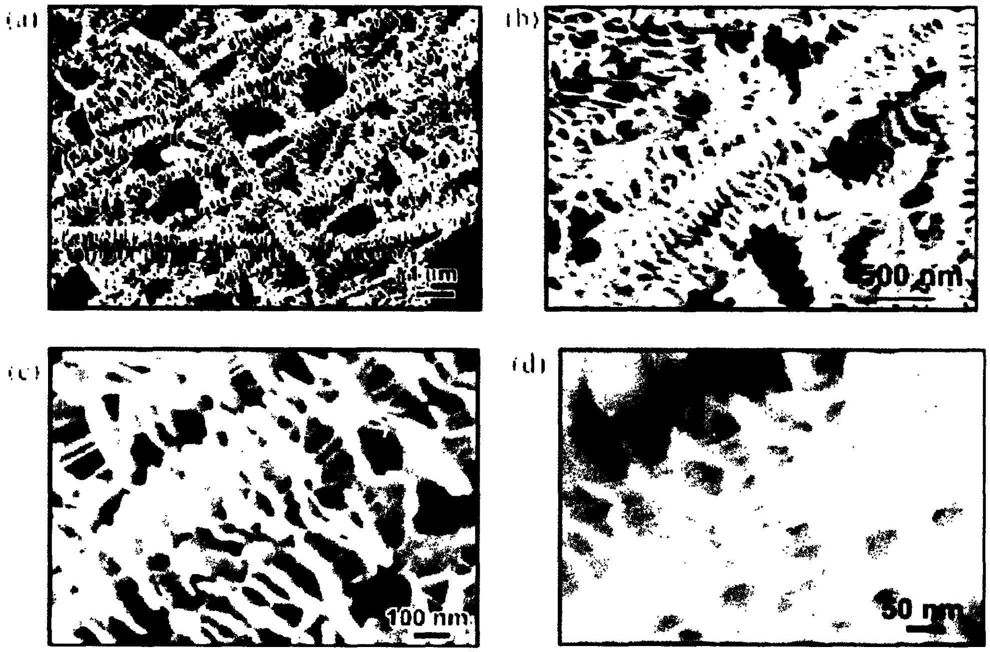

Figure 2: Scanning electron microscopy images of shish-kebab structures. Kebab structures are the lateral, disk-like structures connected by multiple shish structures. (Images from Somani et al. (2005) originally from American Physical Society)

This attempt at characterizing shish-kebab morphology could prove crucial for understanding and designing methods for orienting UHMWPE chains with the ultimate goal of improving directional thermal conductivity. In particular, some studies indicate that the mechanisms required for polymer orientation and shish-kebab formation are dependent on strain rate. Thus, according to these studies, researchers interested in the fabrication of oriented polymers must control for the strain rate of the polymer chain in order to ensure proper morphology (Somani et al., 2005). At the same time, one must note that much of the research on shish-kebab formation is inconclusive (Somani et al., 2005) and will require significant advancements before large-scale manufacturing practices should be based on these characterizations.

## 2.2. UHMWPE thermal studies

Studies have been conducted to understand the factors that affect the thermal conductivity of polyethylene. Different groups have taken different approaches and some of the more notable studies are discussed in this section.

A study in 1995 explored the relationship between UHMWPE chain orientation and thermal conductivity. The study, conducted by Nysten, Gonry, and Issi (1995), tested a large span of draw ratios on PE films and measured their respective thermal conductivities. The samples were drawn at 393°K and draw ratios[2] ranged from 21 to 98. The data, shown in Figure 3, indicated highly anisotropic thermal conductivity in the stretched polymers. For example, a film with $\lambda = 40$ tested at 80°K had an anisotropy factor of thermal conductivity of 26. The results varied with temperature and draw ratio, but generally showed similar anisotropy in thermal conductivity. Furthermore, it was observed that the thermal conductivity

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[2] Draw ratio is defined as the final length of the sample after stretching divided by the initial length

in the transverse direction only decreased slightly while the thermal conductivity in the longitudinal direction increased dramatically. The authors note that the thermal conductivity continues to improve for draw ratios greater than 20 because of an increase in the transverse crystallite size and continued alignment of polymer chains in the amorphous phase. (Nysten et al., 1995)

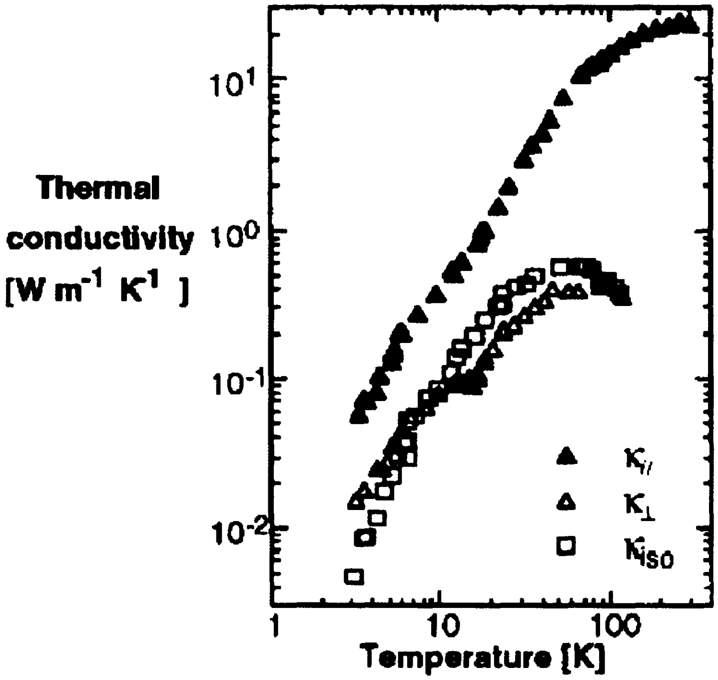

Figure 3: Results from Nysten experiments of sample with λ = 40. Thermal conductivity is shown as ▲ for longitudinal direction, as Δ for the transverse direction, and as ☐ for the unstretched, "pristine" sample. (Adapted from Nysten et al., 1995)

The conclusions reached in the Nysten et al. study are consistent with the findings of a previous study that are shown in Figure 4. In the Anandakumaran study, researchers found that crystallinity increases rapidly as the polymer is stretched. As the draw ratio continues to increase, the crystallinity increases slower and eventually reaches a maximum. (Anandakumaran et al., 1988)

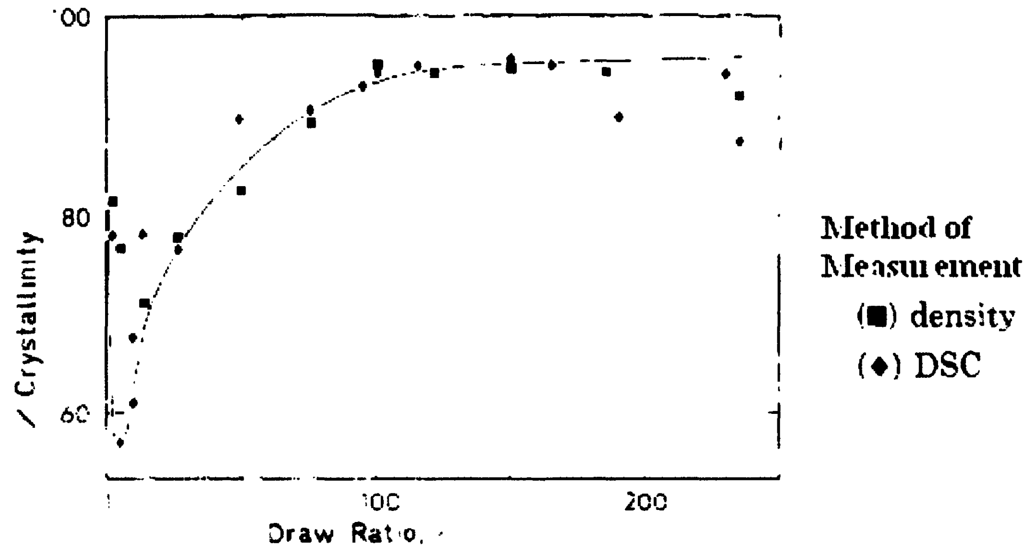

Figure 4: Polyethylene crystallinity is shown for varying draw ratios. Measurements are made from density and heat of fusion methods. Crystallinity increases as the polyethylene stretches until it reaches a limit at a draw ratio of about 100. (Adapted from: Anandakumaran et al., 1988)

While the results from the Nysten et al. study do indicate that stretch-induced polymer orientation can improve thermal conductivity in the direction of stretching, the mechanisms for polymer orientation are not completely clear, and the shish-kebab morphology is not analyzed. Furthermore, the more recent theory of strain rate-induced orientation was not incorporated in these experiments. (Nysten et al., 1995)

A separate study by Sun et al. shows a similar peak for the polymer orientation factor. However, because the study focuses on a different stretching methodology known as dry-spinning, the draw ratios of the Nysten study cannot be directly compared to the after-draw ratios of the Sun et al. study. (Sun et al., 2005)

Studies have also shown that the thermal conductivity of polyethylene is dependent on its molecular weight. Researchers began understanding this phenomenon as early as 1965 when a study (Hansen and Ho, 1965) documented that the thermal conductivity of UHMWPE increases linearly with the square root of the molecular weight until a point where the thermal conductivity levels off. Another study (Kamal et al., 1983) indicated that the relationship between thermal conductivity and molecular weight was also affected by temperature and they proposed an empirical equation that related these terms. (Kamal et al., 1983)

The challenge of determining the optimal draw-down ratio for both thermal and mechanical properties is further complicated by the findings of the aforementioned Sun et al. (2005) study. The study reports that the optimal draw-down ratio might be correlated with the degree of molecular entanglement in the polymer (Sun et al., 2005). If this is the case, researchers and engineers interested in determining the appropriate draw-down ratio for a given polymer would have to consider the degree of fiber entanglement in addition to molecular weight and temperature.

Finally, a study by Minkova tested the effects of radiation on UHMWPE. The study found that radiation does not affect the polymer crystallinity but instead increases the heat of melting. (Minkova, 1988) This information could also be useful for researchers interested in altering the thermal properties of UHMWPE.

## 2.3. Self-reinforcement

Due to substantial interest in UHMWPE for engineering applications, significant research has been conducted to better understand the mechanical properties of the material in addition to the thermal properties. To do so, models have been developed to understand and predict the mechanical behavior of polyethylene. For example, a 1993 study focused on the time-dependent deformation of a commercial polyethylene fiber produced with polymer chain orientation. In this study, the fibers were modeled to have mechanical contributions from delayed elastic and plastic flow components in series, and the proposed model was shown to be accurate to within 10% (Govaert et al., 1993). Similar studies have also been undertaken with other parameters but an in-depth discussion of these models is beyond the scope of this research.

Self-reinforcement research has also been applied to manufacturing techniques and is described in the next section of this report.

## 2.4. Manufacturing and Fabrication

As mentioned above, researchers have investigated methods of improving the Young's modulus of polyethylene by orienting the polymer fibers. Amongst others, two important methods have been used to achieve polymer chain orientation via extrusion methods: melt deformation and solid-phase deformation. Melt deformation refers to the process by which the polymer is heated to a molten state and extruded to cause flow-induced orientation. This orientation is maintained by cooling the PE under pressure. Previous studies have used this method to achieve stretching ratios of up to $\lambda = 35$ on fibers no greater than 25 mm in length (Southern and Porter, 1970). The second method for inducing orientation is solid deformation, in which the polyethylene is extruded while solid at elevated temperatures around 110°C (Pornnimit and Ehrenstein, 1992). This method has been shown in a previous studies to provide draw ratios of up to $\lambda = 16$ (Imada et al., 1971). It should be noted that these draw ratios cannot be directly compared to the higher draw ratios reported in the Nysten et al. study because the Nysten et al. study used stretching methods instead of extrusion methods to induce orientation.

Studies have also been conducted to develop methods to induce and maintain orientation during injection molding and achieve the desirable crystal structure known as shish-kebab structure. While inducing orientation in the extruder is not complicated, maintaining fiber orientation is difficult because it is difficult to control cooling conditions and flow properties during injection molding processes. Nonetheless, methods have been created to overcome these challenges. By increasing injection pressure, the crystallite melting temperature is raised above the die temperature. If these parameters are used with a die that has large flow gradients, the extruded polymer tends to show high fiber orientation. These methods are shown to improve the Young's modulus from 1.4 kN/mm$^2$ to 17 kN/mm$^2$ and improve the tensile strength from 27 N/mm$^2$ to 160 N/mm$^2$. Furthermore, the Pornnimit and Ehrenstein study indicates that polymers extruded with high molecular orientation show improved dimensional stability at high temperatures and homogenous transparency. (Pornnimit and Ehrenstein, 1992)

The Pornnimit and Ehrenstein method of injection molding high-orientation ultra-high molecular weight polyethylene is only one way to attain these characteristics. Another method for fabricating oriented PE fibers is called electrospinning. This method creates thin fibers by exposing dilute polymer solutions to high-voltage electric fields. At the appropriate voltage and distance parameters, the polymer solution will form a jet to the electrical ground, and thus creates a fiber or group of fibers. These fibers have diameters that can range from micrometer scale to hundreds of nanometers. (Hillersborg et al.) Figure 5 shows a sample set up for electrospinning setup.

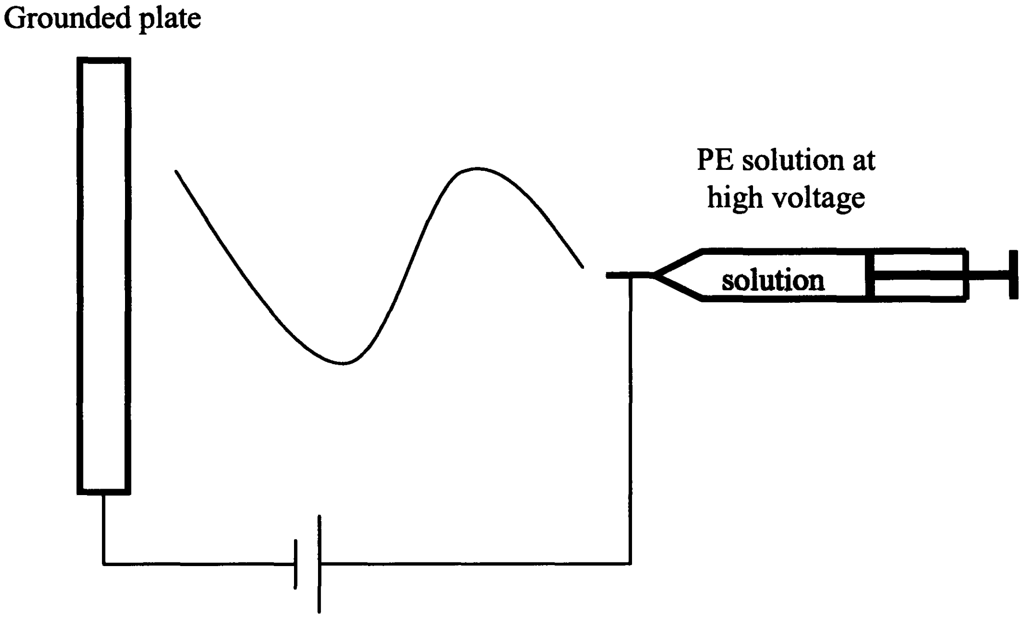

Figure 5: Simplified setup of electrospinning process. A highly oriented polymer fiber is created between the high voltage solution reservoir and the grounded plate.

Another method for producing oriented ultra-high molecular weight polyethylene fibers is known as dry spinning and is used in industrial settings because it produces good fiber quality at low cost. Figure 6 shows a typical dry spinning setup.

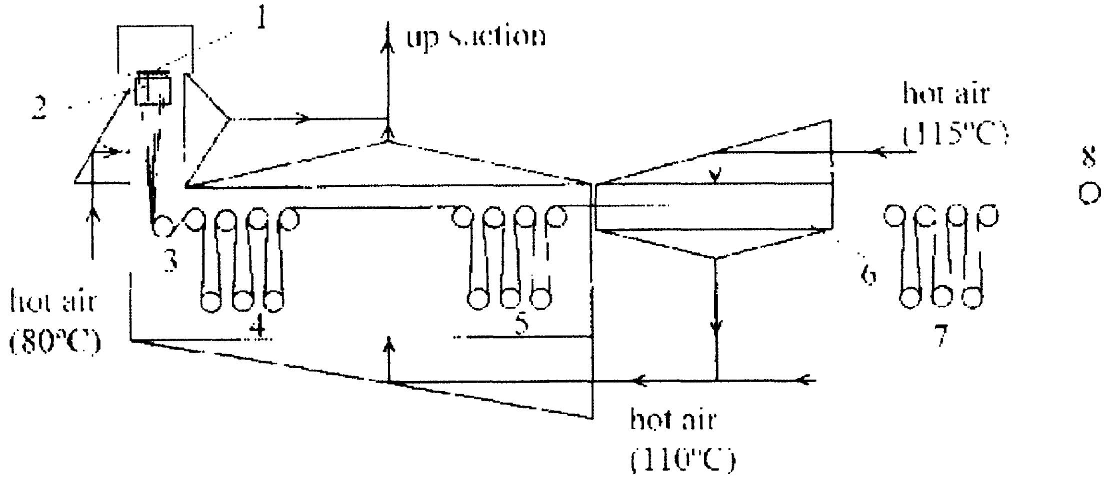

Figure 6: Diagram of typical dry spinning process used for manufacturing highly oriented UHMWPE fibers. (1) spinneret, (2) spinning line oven, (3) guide roller, (4) first roller machine, (5) second roller machine, (6) draw box, (7) third roller machine, and (8) winder. (Source: Sun et al.)

A method called after-drawing is used when processing UHMWPE to disentangle the polymer chains and control the fiber properties after it leaves the spinneret. Research has shown that fibers can be created with optimum draw-down parameters to display the aforementioned shish-kebab morphology, lower crystallinity, and higher melting temperature compared with a free extrusion sample…." (Sun et al., 2005) These characteristics are certainly desirable for many industrial applications and should thus be considered for oriented polymer manufacturing.

Finally, it is worthwhile to mention that manufacturing technology does currently exist for thermoforming polyethylene from solid sheets. For example, industry has developed technology to thermoform high density polyethylene (HDPE) despite the material's technical challenges including its high processing temperature, difficult mold design requirements, and the sag that is induced in the sheet during heating. The additional costs of thermoforming polyethylene are offset by its superior mechanical and thermal properties. (CPChem 2006) At this point, there is no known industrial application of the stretching techniques proposed in the experimental section of this report.

## 2.5. Low Thermal Conductivity Testing Methods

Although the experiment component of this study adopts a chiefly qualitative determination of anisotropy, it is useful to also note that other experimental methods could be employed if further quantitative research is desirable. The primary challenge when quantitatively measuring thermal conductivity in low conductivity materials is accounting for heat losses. In particular, there are three sources of thermal losses that present challenges for such testing: 1) convection of sample and lead wires, 2) radiation of sample, and 3) conductivity through metal lead wires. The first challenge is perhaps the easiest to overcome by testing the sample in vacuum conditions. Second, to overcome the losses associated with the conductivity of lead wires and the radiation of the sample, experiments must be designed in such a way that these heat losses are negligible. In cases where this is not possible, modulated thermal inputs can be used to differentiate thermal conductivity from other thermal transfer mechanisms. Apparatuses exist to perform such experiments and are discussed below.

One apparatus developed for measuring the thermal conductivity of thin fibers uses a heater system to eliminate heat losses caused by lead wires. For each point at which a lead wire contacts the sample, a heating guard is thermally grounded to the lead wire. This guard is maintained at the same temperature as the sample at the point of measurement via a control loop. By maintaining the lead wire and the sample at the same temperature, the conduction through the wire approaches zero. Once this is accomplished, a separate thermocouple can be used to measure the temperature difference between the heating guards. The temperature difference between the heating guards is equal to the temperature difference between the designated points on the sample. (Piraux et al., 1987) This method appears to be satisfactory for minimizing conduction heat losses, but it is unclear how it addresses radiation heat losses.

Another measurement method was used in an automobile parts study in 2000 in which researchers employed modulated differential scanning calorimetry (MDSC) to determine the heat capacity and thermal conductivity of 43 polymeric parts (Abu-Isa, 2000). The study found that MDSC provided quick results that were satisfactory when compared to literature values. (Abu-Isa, 2000) The advantages of the MDSC are derived from its ability to use a modulated thermal input to differentiate between the reversible and non-reversible thermodynamic events. (Carpentier, 2002) An alternative method known as the Angstrom method uses time-modulated thermal inputs to determine the thermal diffusivity of materials.

(Lopez-Baeza et al., 1987) While different experiment design setups are required for different types of Angstrom method experiments, it appears that the short sample, semi-infinite method studied in Lopez-Baeza et al. (1987) could be utilized for thermal measurements on stretched ultra-high molecular weight polyethylene. Regardless of the specific method chosen, special attention should be paid to ensure that the measurement method does not unknowingly alter the structure of the polymer, which would cause errors in the thermal data.

Other thermal conductivity measurement methods are available, especially for thin film experiments, and could be further researched if the aforementioned methodologies are not applicable to the specific experimental requirements.

# 3. Experiment

Thus far, this report has focused on surveying past research efforts. In this section, original experimental results are reported for a preliminary stretching method for UHMW-polyethylene.

## 3.1. Purpose

The experiments conducted were designed to explore the feasibility of stretching pre-fabricated sheets of ultra-high molecular weight polyethylene (UHMWPE) for the purpose of improving its thermal conductivity in the direction of stretching. This method is a variation from the research discussed earlier in this report, as most research has focused on orienting polymer fibers rather than sheets. This study also considers the implications on the manufacturability of stretched UHMWPE. While other polymers were considered for testing, UHMWPE was chosen due to its widespread use in industry and its high polymer chain length which facilitates stretching. If this type of experiment shows satisfactory results, it could be used in the development of a process for stretching and forming UHMWPE in a manner similar to conventional thermoforming.

## 3.2. Experimental set-up

Commercial sheets of UHMWPE were purchased from a commercial vendor[3] at varying thicknesses. Because of the low-friction and high strength qualities of UHMWPE, the process of determining the optimal stretching method was difficult. To properly stretch the material without reaching failure, the material was heated and placed under tensile load. However, UHMWPE was observed to undergo a phase transition at approximately 140°C at

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[3] UHMW-Polyethylene sheets were purchased from McMaster-Carr Supply Co.

which the material was observed to fail under tensile loads that would otherwise not cause failure. At this temperature, the material also became transparent. For this reason, temperature control became the most critical factor for developing an effective stretching method. Several methods were attempted and are explained below, and ultimately a method using oil to create a stable heating environment was used.

The first method considered for stretching the polyethylene was convection heating in an oven. A strip of PE film was fastened to a stretching mechanism shown in Figure 7 and the entire assembly was placed inside a convection oven. After the system had equilibrated, the assembly was used to stretch the strip of PE. After each stretching, the oven and assembly was allowed to equilibrate before the next stretch was conducted. This method had three major shortcomings: first, it required opening the oven to stretch the material, and thus caused non-uniformities in the convection of the oven. Second, it was very difficult to mount the UHMWPE to the assembly because at these temperatures, the sample easily slipped from the assembly. Third, stretching was conducted in discrete non-repeatable steps that would not provide useful information regarding strain rates. Despite these factors, samples were stretched to approximately 4 times the original length. After additional stretching, this method caused the samples to break. For this reason, this method was not used.

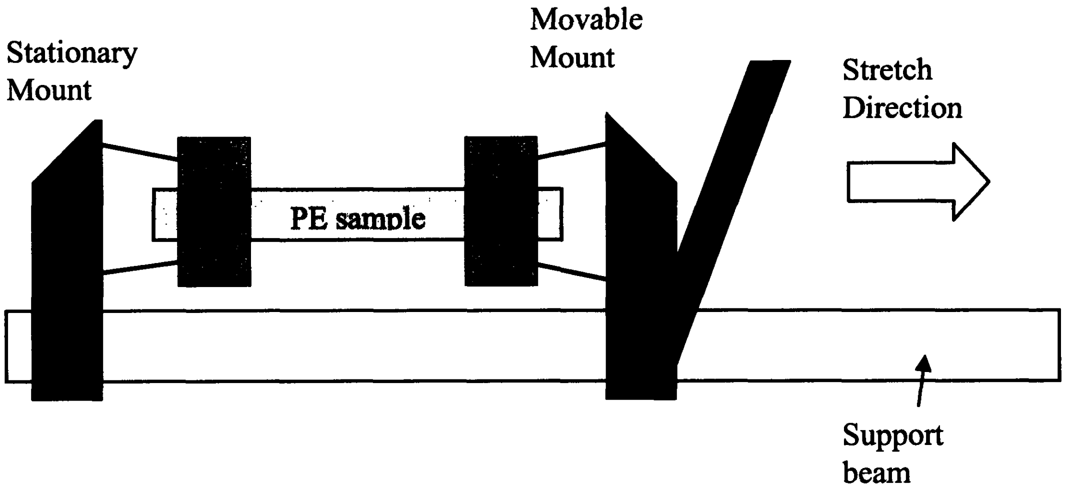

Figure 7: Diagram of original stretching device. This device was not used for samples reported in these results.

The second method attempted to minimize the non-uniformities in the oven involved utilizing local heating in the middle of the sample. This allowed for the mounting mechanisms of the assembly to remain at room temperature for improved grip. It was also expected that locally heating the sample would eliminate the unpredictable convection patterns experienced when opening the door of the oven. Upon testing this method, it was noted that the PE heating was still irregular and the polymer failed at undesirably low strain levels as a result of irregular heating. Furthermore, this method made it difficult to accurately calculate total strain because the amount of polymer being heated changed as it was stretched. For these reasons, this method was not used in the final experimental setup.

The convection heating methods were then modified to use contact heating. Copper plates were placed on both sides of the polymer and were heated with electrical heaters. The stretching assembly was maintained outside of the heating process, and thus, the mounting mechanism remained at room temperature and did not allow slipping. Initial experiments showed that the contact heating was also irregular. Samples failed due to the heating irregularity as they had in the previous setups. In an effort to improve thermal contact, thermal grease was used on the copper plates, but this was unsuccessful at providing repeatable, controlled samples.

Finally, a method was developed to control the thermal environment of the polyethylene using oil heating. A new stretching device was assembled to stretch the sample around a shaft. This assembly was then submerged in a heated bath of corn oil. Thermal insulation was placed between the sample and the metal components of the device to avoid temperature irregularities. Furthermore, a thermocouple was used to test the temperature variances throughout the oil bath, and they were observed to be no greater than 0.5°C. This provided a significant improvement on previous methods and the improvements to the mounting components of the assembly allowed for a safe, effective stretching process. Under these well controlled heating conditions, the final samples were stretched around the central axis.

Two devices were used for this final method of polymer stretching. The significant difference between each setup is the axis of rotation, which is adjusted in the second setup to allow for the mounting clips to be maintained outside of the oil bath. It is important to note that the stretching was not uniform throughout the sample because the multiple points of contact between the polymer and the device caused various frictional forces. For this reason, the strain value for the polymer is reported as an approximate value.

Once the sample was stretched, it was removed from the oil bath and allowed to cool in ambient conditions. The portion of the sample with the highest observed strain was cut and used for thermal experiments.

### 3.3. Thermal Conductivity Measurements

Measuring thermal conductivity in low-conductivity materials can be difficult because of the complexities of controlling for convection and radiation losses as well as losses through thermocouple probes. Because determining an exact value of the thermal conductivity was beyond the scope of this research, the samples were tested using infrared microscopy to determine the anisotropy of thermal conductivity in the polymer. A point source heater was built using a short copper probe connected to an electric heater and a controller. The copper probe was contacted to the sample from the underside of the PE strip, as shown in Figure 8:

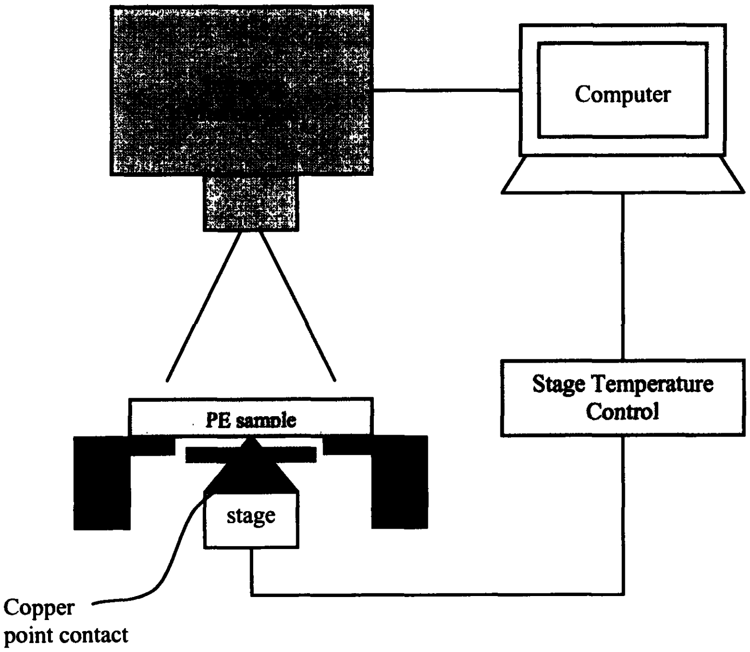

Figure 8: Diagram of Experimental Setup. Polymer was heated from below by computer controlled stage and images were taken by infrared microscope. The blue line shown intersecting the copper point contact represents the radiation insulation placed between the heater and the sample.

As shown in the diagram, a small piece of cardboard was used to insulate the sample from the radiation and convection from the heating element.

The Infrascope II[4] infrared microscope was set up using a 1x objective. Because the experiment was focused on relative thermal properties and because the quantitative infrared properties of the sample were not known, the radiance setting on the infrared microscope interface was arbitrarily set to 1.00. This indicates that the absolute values of the temperatures measured are not valid, but the relative values are. For this reason, temperature values are not reported in the results section.

### 3.4. Results

The infrared experiment indicated that the stretched polymer did indeed show anisotropic temperature profiles while the unstretched sample did not. Stretched samples showed increased thermal conductivity in the direction of stretching. Figures 9 and 10 shows sample images attained for data analysis.

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[4] The model number of the Infrascope II infrared microscope used was IRRIS-256LN. Microscope software was Infrascope II Version 2.4a which is a copyrighted product of Quantum Focus Instruments.

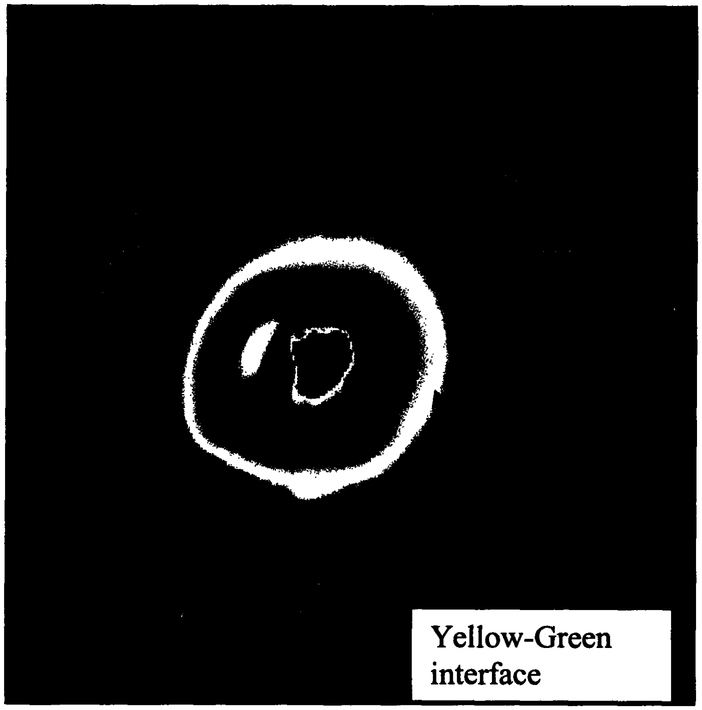

Figure 9: Infrared image of unstretched UHMWPE with point heater at 100°C applied at the center of the image. Note that there is no significant anisotropy in the temperature profile.

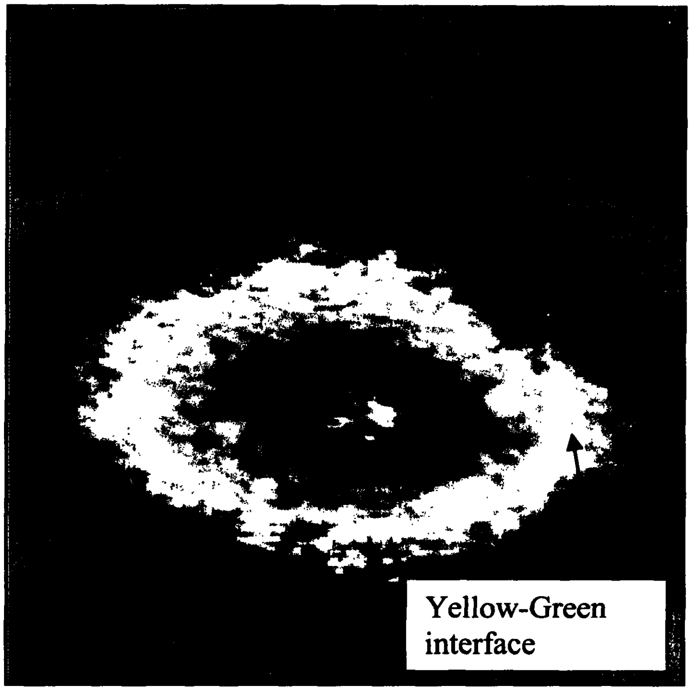

Figure 10: Infrared image of stretched UHMWPE with point heater at 100°C applied at center of image. Draw ratio is approximately $\lambda \approx 10$. Note the significant anisotropy in temperature profile. The yellow-green interface is noted for its use in the data analysis.

The anisotropy value was determined by comparing the size of the yellow-green interface of the infrared image. This interface was determined to be the clearest, most consistent method for comparing different samples. For the sample of draw ratio $\lambda \approx 10$, an anisotropy of thermal conductivity was measured to be 1.4.

## 3.5. Discussion

The infrared images demonstrate the existence of anisotropic temperature profiles in the stretched polymer. Several potential causes of uncertainty are considered and discussed in this section. First, the use of an arbitrary radiance value should not raise concern because the portion of the sample directly above the copper point probe was the only portion that had a significantly different infrared radiance than the rest of the sample. Because conclusions were not drawn from this portion of the sample, there is no reason to believe the arbitrary radiance values are a cause for concern. Second, the proximity of the electrical heater to the sample is shown not to affect the validity of the results. Figure 11 shows that the addition of insulation between the heater and the sample was effective at mitigating this concern.

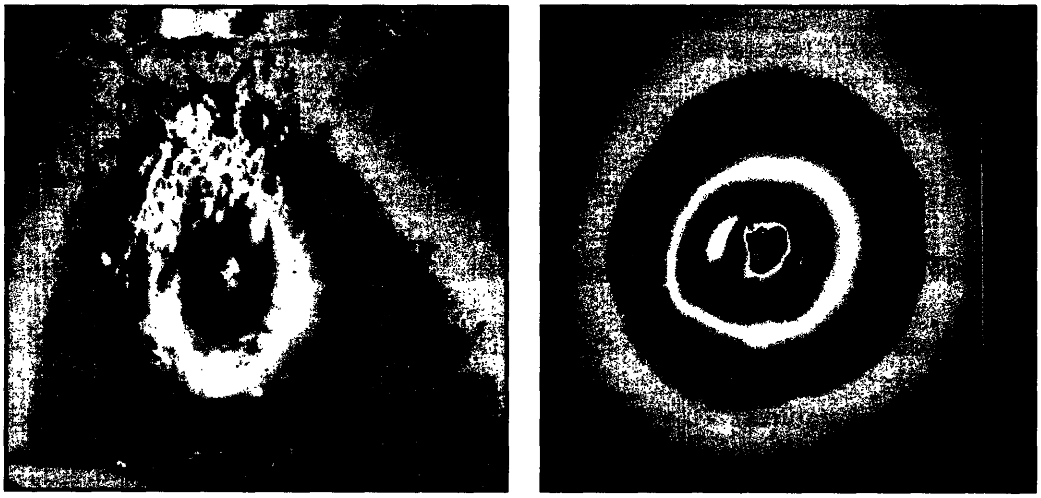

Figure 11: Infrared image of preliminary UHMWPE tests without insulation between heater and sample (left) and with insulation (right). Note the irregular, asymmetrical heating pattern caused by radiation and convection heating of the sample. This problem was solved with insulation and the result is shown on the right.

The third consideration for uncertainty in the results is the effect of radiation and convection losses on the sample. Because the sample was not tested in a vacuum environment, it was exposed to convection losses. Because the absolute temperature profile is not known for the sample, it is not possible to make a precise calculation of these losses. For this reason, this study can only conclude qualitatively that thermal conductivity anisotropy was induced.

Despite the qualitative nature of the results, it is clear that the magnitude of the anisotropy is not as high as the anisotropy ratios that the Nysten et al. study reported for their experiment. The Nysten study indicated that thermal conductivity could be improved by a factor of 20 at a strain ratio of 40. (Nysten et al., 1995) Unfortunately, this study was unable to attain strain ratios similar to those of Nysten, and thus the comparison is not ideal and the results are of significantly different magnitude.

The differences between these results and the Nysten et al. study may be caused by a variety of factors. First, the difference is believed to be affected by the much higher polymer orientation of the Nysten et al. samples due to a higher draw ratio. Unfortunately, the magnitude of this effect is not measurable because this study did not provide samples of similar draw ratios. Second, the polymer stretching techniques for the studies were quite different. While the Nysten et al. study reported solid-state drawing at 120°C on hot shoes, samples used in this study were drawn at temperatures ranging from 137°C to 145°C. Attempts were made to stretch the material at temperatures closer to the Nysten et al. values, but the polymer would not deform at such temperatures. This leads to a third difference between the studies: polymer composition. Because polymer chain size and degree of entanglement varies between different UHMW-polyethylenes, it is possible that differences in the polymers used caused different results. Fourth, as mentioned before, there was a significant amount of uncertainty in the strain measurements made in this experiment. While this would not explain all the differences in results, it could be one of several factors that contributed to variations.

# 4. Conclusions

The results of this experiment indicate that engineers could apply UHMWPE stretching techniques in thermoforming processes to increase thermal conductivity in the direction of stretching. For samples with draw-ratios of approximately 10, thermal conductivity in the direction of stretching increased noticeably. The thermal conductivity in the direction perpendicular to stretching was not observed to change. Furthermore, this study coupled with previous studies indicates that in order to obtain higher thermal conductivity values, researchers should develop improved stretching techniques. Further research could also be conducted in understanding the formation of the desirable shish-kebab morphology in UHMWPE. If these improvements are made, high thermal conductivity thermoforming could be implemented for manufacturing.

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