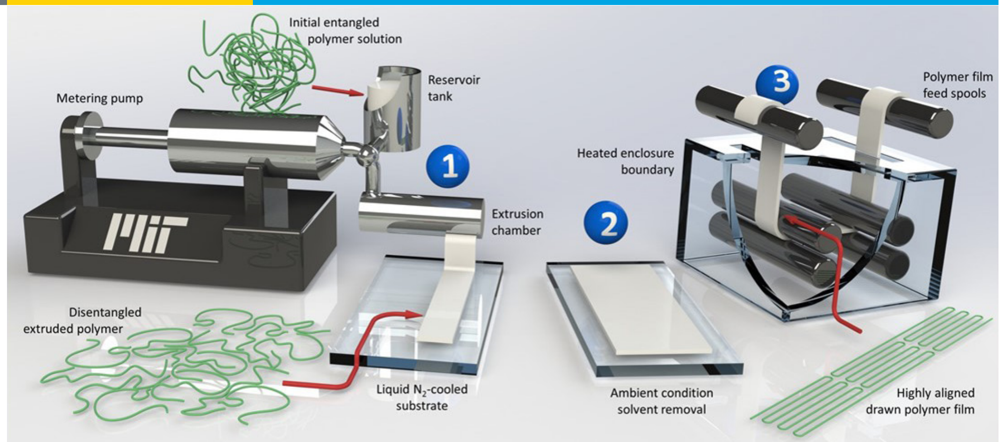
Continuous Processing of High Thermal Conductivity Polyethylene Fibers and Sheets



Researchers developed a 3-stage continuous fabrication process for high thermal conductivity polyethylene films. *Image courtesy of MIT*

A Lightweight Material for Thermal Management Applications

Introduction

Thermal conductivity is an important consideration in choosing materials for different manufacturing applications. For example, materials used in heat exchangers require high thermal conductivity because heat must be transferred between mediums located at a distance from one another. Historically, heat exchangers have been manufactured from metal because they are effective in conducting thermal energy. Plastics, although cheaper, lighter, and less energy intensive to make than metals, are much less efficient in conducting heat than metals. This project combined the valuable performance characteristics of both metals and plastics by developing a continuous production process for ultra-high molecular weight polyethylene (UHMWPE) fiber and sheet production that resulted in a thermally conductive plastic material.

A number of lab-scale studies have shown that thermal conductivity is improved when polymer fibers are stretched mechanically. This increase is believed to be a direct result of the higher molecular chain alignment achieved by stretching. The aim of this work was to transform these early laboratory results into a scalable production process.

The production process used an extrusion chamber designed for sheet formation to extrude an UHMWPE solution at a set temperature and shear rate. The extruded solution flowed immediately onto a liquid nitrogen-cooled substrate, and the resultant gel was then exposed to a controlled temperature environment to partially evaporate the solvent and solidify the gel sheet. The sheet was reheated and stretched inside a heated enclosure to enhance the molecular chain orientation and create high thermal conductivity. A combination of process modeling and experimental trials were used to identify conditions that yield plastic sheets with high thermal conductivity.

The thermal conductivity of the fibers and sheets was 100 to 1,000 times greater than that of bulk polymers and at least twice that of current commercially available fibers.

Benefits for Our Industry and Our Nation

Benefits are expected to be realized in both fabrication and end use of the material. Energy intensity will be significantly lowered during material synthesis and processing because lower process heating temperatures will be used. The result will be that production plants for these materials will generate less pollution compared to metal processing plants. These polymers could be a game changer for many heat exchangers, especially in fins that require directionally high thermal conductivity values. They also could be used in thermal management systems in microelectronics, where an electrical insulating material is preferred. High thermal conductivity sheets could significantly expand the potential uses for plastics and could help the U.S. plastics industry improve its competitive position internationally.

From an end use perspective, polyethylene is 35% less dense than aluminum, making the material lighter per unit volume. For example, using these polyethylene sheets in automotive applications would reduce vehicle weight and improve fuel economy.

Applications in Our Nation's Industry

This process could provide the plastics industry with a low-energy, cost-effective method of producing high thermal conductivity polyethylene material for further use as a lightweight and inexpensive alternative to metals in various heat transfer applications. Process integration is simplified by existing knowledgebase and widespread use of polyethylene.

Project Description

Project tasks focused on manufacturing platform design and fabrication, process modeling and optimization, materials characterization, and property characterization and modeling. Ultimately the project successfully developed and validated a continuous manufacturing process for polyethylene fibers and sheets yielding a thermal conductivity value greater than 60 watts per meter-Kelvin (W/mK).

Barriers

- Lack of scalable processes for manufacturing high thermal conductivity polyethylene sheets.
- Uncertainties associated with molecular-scale chain engineering and modeling.
- Understanding of the optimum conditions for proper polymer flow through the extrusion chamber to limit or eliminate clogging.

Pathways

The primary task involved manufacturing platform design and fabrication. The concept was based on a gel-extrusion process and subsequent hot drawing. Research efforts focused on fabricating and assembling the processing apparatus. Process modeling and optimization were conducted to guide the manufacturing process considering four key variables: shear force of the extrusion chamber, Couette flow of the polymer through the chamber, polymer drying, and optimal draw ratio.

Researchers characterized the structure of the polymer chains within the finished product using techniques such as X-ray diffraction, polarized microscopy, scanning electron microscopy, and transmission electron microscopy.

Researchers also conducted property modeling to determine the thermal conductivity of the polymer sheets, specifically focusing on discovering the heat transfer characteristics between the polyethylene chains. These models will provide guidance for structure and process optimization to advance the technology.

Milestones

This project began in 2012 and was successfully completed in 2016.

- Achieve capability to fabricate greater than 1 × 5 square centimeter (cm^2) polymer sheets by means of the proposed gel-extrusion and hot drawing process.
- Reach a thermal conductivity greater than 30 W/mK in 1 × 5 cm^2 sheets.
- Reach a thermal conductivity greater than 60 W/mK in 1 × 10 cm^2 sheets.

Accomplishments

- A computational model to improve the extrusion process was developed; the model is capable of simulating a non-Newtonian fluid for viscosity that spans several orders of magnitude.
- A continuous drawing platform with controllable draw rate and ratio was designed and fabricated.
- In-plane thermal conductivity value of 62 W/mK—higher than most ceramics and metals—was achieved in polyethylene sheets that are meters long and centimeters wide.

Commercialization

There is strong interest from major chemical and polymer producers regarding this high thermal conductivity polyethylene material. The Massachusetts Institute of Technology (MIT) intends to secure intellectual property for this technology, then determine whether to license it directly to other companies or pursue another commercialization option. As a first step in this process, the research team engaged students in the MIT Sloan School of Management. As has been the case for numerous MIT technology developments, there is a strong possibility that a start-up company could be formed by project participants to further advance the technology.

Project Partners

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