In 2008, a National Science Foundation panel committee identified five areas in which societal needs pose substantial technological challenges and where polymer science will play a crucial role in providing solutions, with first two areas being sustainability and energy. The panel concluded that a sustainable polymer industry will provide biodegradable and renewable polymers. Because most near-future polymers will be petroleum based, these materials can be made greener by optimizing their processing and recyclability. The panel also concluded that polymers will serve as novel energy generating and storage systems. In the summer of 2009, our two-person team addressed sustainability- and energy-related issues in polymer science by taking advantage of unique capabilities developed in Prof. John Torkelson’s group on the use of a novel, industrially scalable process called solid-state shear pulverization (SSSP). Previous work in Torkelson’s group using SSSP to process polymers and hybrids/composites has resulted in minor-phase dispersion and enhanced properties that cannot be achieved by conventional processes, e.g., melt-state processing.

Polylactic acid (PLA) is a renewable, biodegradable polymer with potential to replace petroleum-based polymers used in disposable, hot food and beverage containers. Interest in that application is driven by regulations in some countries that will require food waste, including disposable containers, to be composted. Amorphous PLA undergoes major distortions at 60 °C, its glass transition temperature. Thus, if hot coffee were poured into a rigid, amorphous PLA cup, upon warming up the cup could deform and crumple. When semi-crystalline, PLA maintains its shape and mechanical integrity below the melt temperature of 160 °C. However, because neat PLA has a very slow crystallization rate, it cannot be processed by injection molding when the desired product needs to be semi-crystalline. Our goal was to use SSSP to add and disperse low levels of a renewable, biodegradable material, microcrystalline cellulose (MCC), in PLA; our hypothesis was that the MCC/PLA interfaces would nucleate PLA crystallization and transform the crystallization rate from grudgingly slow to rapid. Our results confirmed our hypothesis, even with 1 wt% MCC content. Although the process method is not yet optimized, we found that a 1-3 minute annealing step allows the MCC/PLA hybrids made by SSSP to achieve the maximum possible PLA crystallinity. Refinement of the SSSP process may allow use of such hybrids in injection molding of semi-crystalline PLA materials that meet all requirement of high-temperature mechanical integrity and compostability for disposable food and beverage containers.

We also did sustainability research on polycaprolactone (PCL) and poly(ethylene terephthalate) (PET), the former used in biomedical products and the latter in beverage containers and as synthetic fibers. Our main goal was to increase the sustainability of PCL and PET by using SSSP to increase their crystallization rates while maintaining or improving other properties. Relative to unprocessed polymer, we found that SSSP processing reduces PCL crystallization times by 50%. This increase in crystallization rate can substantially reduce cycle times (and use of energy) in molding PCL products. We showed via rheological measurements that the increase in crystallization rate in PCL caused by SSSP processing can be achieved simply by better dispersion of heterogeneous nucleation agents naturally in PCL without need for mechanochemistry, i.e., mechanically induced chain scission. In contrast, with PET, SSSP-induced mechanochemistry can result in linear PET chains transforming into lightly branched PET, with an accompanying fall in PET crystallization times of 70% and a rise in melt viscosity. This latter effect provides a solution for the problem of recycling PET for high-value applications, because melt processing of PET is accompanied by hydrolysis leading to molecular weight reduction. This means that once PET is melt-molded, its viscosity is too low to allow recycling of that PET in the same operation. Processing recycled PET by SSSP solves that problem.

We also did energy-related research aimed at producing highly electrically conductive polymer composites for use as bipolar plates in fuel cells. Bipolar plates are currently made from graphite and are heavy, difficult to machine, and brittle. The U.S. Department of Energy (DOE) has a goal of developing polymer composites that can be easily and inexpensively processed into bipolar plates and that have high conductivity (> 100 S/cm). A major challenge in preparing such a composite is the dispersion of graphite or other carbon-based conducting material in the polymer. Our solution was to use SSSP to pulverize polypropylene (PP) into a fine powder with high surface area. Simple hand mixing allows high levels of powdery graphite to be dispersed in PP powder. Using a mix of 70 wt% graphite/30 wt% PP powder, we made composite films with electrical conductivity of 6.2 S/cm, equal to the maximum conductivity of the neat graphite used in the composite. If we use a carbon-based filler with conductivity equal to or greater than 100 S/cm, we believe that we can meet the DOE goal using PP-graphite composites.