

# Microcellular Injection Molding of Biobased/Biodegradable Plastics

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*ABSTRACT: This report addresses the research experience gained through the International Research in Education and Engineering (IREE) program sponsored by National Science Foundation (NSF). By collaborating with the Microcellular Processing and Manufacturing Laboratory at the University of Toronto, Canada, we demonstrated how modification of polylactide (PLA) with some additives such as chain-extender, hyper branched polymer, and biodegradable poly(butylene adipate-co-terephthalate) (PBAT) will improve the properties of PLA. The report presents several representative results obtained from the study on the PLA/chain-extender series. Finally, the report concludes by highlighting the extended benefits that this international collaboration has provided.*

## INTRODUCTION

Although biodegradable and sustainable biobased plastics have been successfully produced from renewable resources, their commercial applications have been limited primarily due to their inferior material properties, narrow processing windows, and relatively high material costs. Both microcellular extrusion and microcellular injection molding processes are capable of producing microcellular-foamed plastics with less material and energy, and potentially improving its material properties such as impact strength and fatigue life. In addition, both processes allow the material to be processed at lower temperatures and pressures, making it suitable for temperature-sensitive biobased plastics and/or additives. Therefore, microcellular processing (both extrusion and injection molding) of biobased plastics not only improves processing economy and part performance but also enhances processability and application areas.

An IREE grant was awarded to the University of Wisconsin-Milwaukee. Extensive experimental and analytical work has already been conducted to study the effects of various additives, including nanoparticles (e.g., nanoclays and carbon nanotubes) and natural fibers, as well as the processing parameters on the cell morphology and material properties of biobased polymers.

This IREE project on the microcellular extrusion of biobased plastics is within the larger scope of our current NSF-funded project on the microcellular injection molding of biobased plastics. While these are two different processes with different characteristics, studies on these two microcellular processes share the same goal--to broaden the applications of biobased plastics. Although the collaborating institute is equipped with both microcellular extruder and microcellular injection molding machines, microcellular extrusion was chosen to broaden the research experience of the students at UWM.

Our host laboratory is the Microcellular Plastics Manufacturing Laboratory (MPML) at the University of Toronto. The world-renowned facility is likely the world's largest academic research group that develops innovative microcellular technologies. MPML has several state-of-the-art microcellular processing and characterization tools, including a microcellular injection molding machine, a microcellular extruder, a microcellular rotomolding machine, a twin-screw extruder for melt compounding, a magnetic suspension balance (MSB) for measuring the solubility of supercritical fluids (SCFs) such as N<sub>2</sub> and CO<sub>2</sub> in polymer melts, and a rheometer.

One graduate student (Srikanth Pilla, 05/26/07-08/13/07) and one undergraduate student (George Auer, 05/26/07-07/27/07) at UWM are working on the project related to the microcellular injection molding of biobased plastics. Their research focuses on characterizing the microcellular plastic components that are injection-molded at our collaborating institute, the University of Wisconsin-Madison, to establish the composition-process-structure-property relationship and advance the understanding of cell nucleation and growth mechanisms. Through this grant, the students conducted research at MPML with Prof. Park during the summer of 2007 and gained first-hand experience with several key polymer processes, including microcellular extrusion and melt compounding. They also had the opportunity to use several key characterization tools for microcellular technology. Funding from this grant will continue to expose both students to all aspects of the research on biobased polymers starting from formulation, to melt compounding, microcellular processing, and characterization.

### **RESEARCH ACTIVITIES AND ACCOMPLISHMENTS OF THE INTERNATIONAL COOPERATION**

Three series of formulations were designed to be carried out during the international research experience:

1. Effect of adding epoxy functionalized chain-extender on the cell morphology and weight reduction of PLA:

One of the major obstacles faced by PLA foaming is the lack of enough melt strength. This was addressed by adding an epoxy functionalized chain-extender, which came as a PLA master-batch and was originally produced by Johnson Polymers. It is highly effective in improving the melt strength for polyethylene terephthalate (PET).

2. Effect of hyperbranched polymer (HBP)/polyanhydride (PA) on the cell morphology and weight reduction of PLA:

Brittleness is one of the inferior properties that pure PLA possesses and greatly limits its applications; however, previous studies conducted by Bhardwaj and Mohanty [1] found that adding HBP/PA (which may form an interpenetrating network (IPN) structure within the PLA matrix) can greatly improve the impact strength of PLA. Lin et al. [2] used only HBP to enhance the toughness of PLA. We aim to find out how adding HBP/PA affects the foamability of PLA in addition to its direct impact on the toughness of PLA.

3. Effect of adding poly(butylene adipate-co-terephthalate) (PBAT) on the cell morphology and weight reduction of PLA:

Previous studies [3-4] carried at MPML revealed that the addition of a second polymer has a significant impact on the cell morphology (open/closed) and material properties. Poly (butylene adipate-co-terephthalate) (PBAT) was chosen for this study because (1) it is tougher than PLA and (2) it is biodegradable. Since PBAT is immiscible with PLA, a commercially available PLA/PBAT blend also was used to study the effect of compatibilization on the cell morphology and other microcellular extrusion properties. In addition, a ladder study of PBAT was conducted to evaluate the effect of different proportions of PLA over PBAT on the said properties. For all the studies, talc was added as a nucleating agent to provide good heterogenous nucleation.

Although microcellular injection molding and extrusion are two different processes, the effects of various additives have a similar impact on the cell morphology and the material properties of the foamed products. The original scope of the grant is on microcellular injection molding; however, what we have learned through this study on microcellular extrusion will be applied and tested for the microcellular injection molding process in the near future.

As mentioned previously, the MPML is well equipped with all the necessary facilities to carry out the above experiments. These studies were conducted with the help of S. G. Kim, a graduate student of Prof. Park, who trained us on all the processing and characterization equipment involved with this project. Meanwhile, Prof. Gong and Prof. Park have communicated extensively and regarding the design of the formulations, the analysis of the experimental results, and the presentation of the findings. Several representative findings obtained for the first set of experiments, i.e., the effect of adding chain-extender on the cell morphology and weight reduction/volume expansion on PLA, are provided below.

Figure 1 shows the effect of chain extender on the volume expansion of PLA, and Figure 2 shows the same with the open cell content. As can be inferred from Figure 1, at the same die temperature, the volume expansion ratio increased with an increasing CE content until a stable value was reached. The volume expansion did not vary much with change in die temperature for all formulations except PLA-1.0%CE and PLA-1.3%CE. This suggests that the CE content was too low for materials below 1.0%CE. For formulation above 1.3%CE, the material could not be processed at lower temperatures due to an increase in viscosity and melt strength. The volume expansion ratio of pure PLA was 1.7 and the maximum volume expansion ratio of approximately 3.8 was achieved for PLA-1.0%CE and PLA-1.3%CE extruded at 130°C.

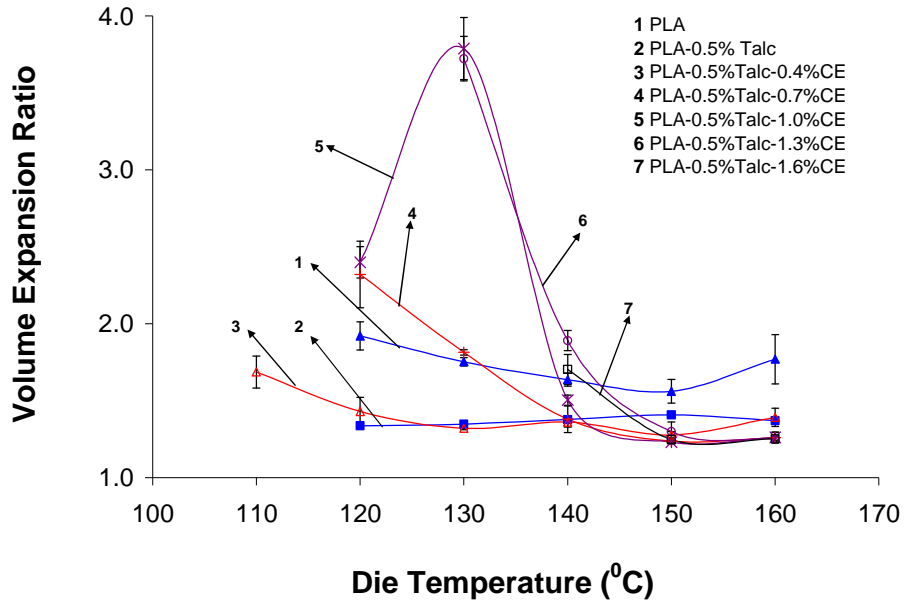


Figure 1: Variation of volume expansion ratio with temperature for varying chain-extender content

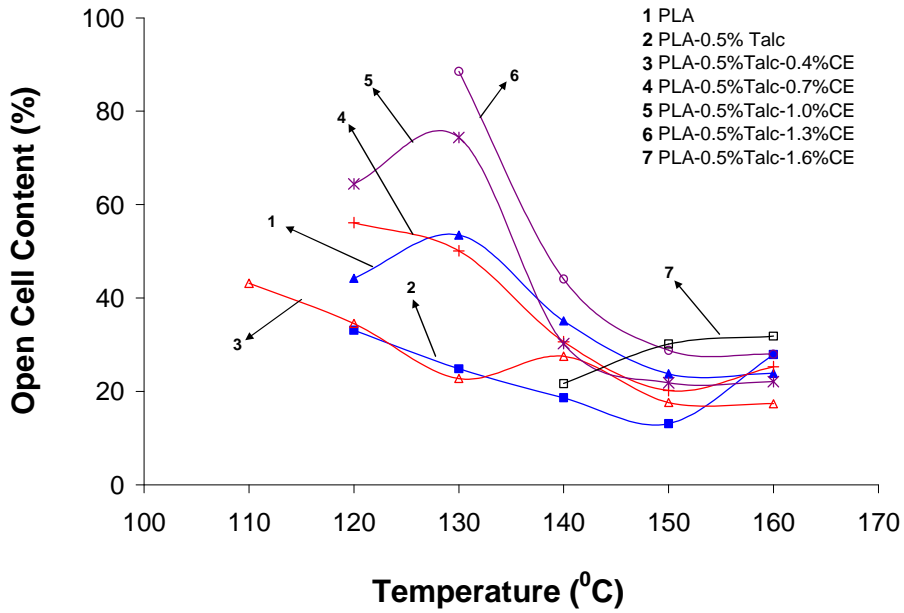


Figure 2: Variation of open cell content with temperature for varying chain-extender content

In general, the open cell content (Figure 2) increased with decreasing die temperature; however, this increment was not significant at lower concentrations of CE. At a lower percentage of CE, the open cell content was generally less than that of pure PLA. However, as the concentration of CE increased to 1.0% and 1.3%, the open cell content generally became higher than that of pure PLA. The highest open cell content of 88% was observed for PLA-1.3%CE extruded at 130°C and the next highest of 74% for PLA-1.0%CE extruded at same processing temperature. This increment of open cell content for these two (1.0%CE and 1.3%CE) materials might be due to the thinning of cell walls that occurred as a result of the increased expansion ratio.

## **BROADER IMPACTS OF THE INTERNATIONAL TRAVEL**

Continuous microcellular processing techniques could enable the mass production of environmentally benign, biobased plastic components with improved material properties and reduced material cost. By collaborating with the MPML at the University of Toronto, we not only investigated the microcellular injection molding process as proposed in the original grant application, we also investigated the microcellular extrusion process, thereby greatly expanding the original scope of the current award. This extended research will help us to broaden the applications of biobased plastics in the areas of packaging, structural, and biomedical devices and ultimately help the U.S. agriculture, forestry, and plastics industries to gain a competitive edge in the global market. The resultant technology also will be transferred to local and regional industry partners via the UWM Office of Technology Transfer.

Moreover, this project has given two students the opportunity to work in a first-class polymer research laboratory and gain hands-on experience with several key material processing and characterization tools. This team at UWM also has benefited greatly from collaborating with a world-renowned professor and his research associates with various expertise related to microcellular technology, and from the exposure to a different culture and research environment.

As a result of this collaboration, one joint paper, "Effect of Adding Epoxy Functionalized Chain-Extender on the Cell Morphology and Volume Expansion of Polylactide Using the Microcellular Extrusion Foaming Process," was presented during *BIOFOAMS-2007*, Capri (NA), Italy, September 26-28, 2007. Our team also has been invited to publish a paper on this work in a special edition of the *Journal of Cellular Plastics* on biopolymers. Another paper, "Microcellular Extrusion of Poly(lactide)/Poly(butylene adipate-co-terephthalate) Blends: Part-1. Effect of Compatibilization on the Cell Morphology and Volume Expansion," was submitted to *ANTEC 2008*. In addition, the PI and Dr. Park have collaborated on a book chapter related to microcellular injection molding that is to be published in 2008.

The collaboration with Dr. Park also has fostered a strong, productive partnership in the field of biobased materials between the PI's Polymer Engineering Laboratory at UWM and the MPML at the University of Toronto. Dr. Park, who is greatly impressed by the two visiting students' performance as well as the types of research projects engaged by the PI's team, has extended a standing welcome to visit his laboratory and conduct

additional collaborative research at any time. Mr. George Auer, the undergraduate student, has enjoyed the research experience greatly and has decided to pursue graduate school study after this visit. He also is taking an independent study on biopolymers with the PI during the fall 2007 semester.

## DISCUSSION AND SUMMARY

The international research experience has given us an exhilarating experience and directly connected us with one of the best laboratories in microcellular processing. The hands-on experience we gained at MPML was the first of its kind and added value to our research. The experience has considerably broadened our knowledge base in microcellular processing, especially in extrusion. The research collaboration has explored a new arena in the processing of biobased materials via microcellular extrusion, as we were able to demonstrate with experiments how PLA can be modified and in what quantities to make it compete with existing non-biodegradable and fossil fuel-based commodity plastics. This will help to make the world “greener” and also extend the time period for which depleting fossil fuels remain.

The IREE program in its current state is in good shape to motivate young and enthusiastic researchers to work with world-class scientists and facilities; however, additional funding would be deeply appreciated for continuous collaboration in the following years. Such long-term collaboration would foster more in-depth investigation of certain projects.

## ACKNOWLEDGEMENTS

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## BRIEF BIOGRAPHIES OF RESEARCHERS

**Srikanth Pilla** is currently a doctoral student in the Department of Mechanical Engineering at the University of Wisconsin-Milwaukee, USA. Earlier he worked at S.C. Johnson and Son, Inc., where he participated in the invention of a home cleaning product and now holds a US provisional patent for the same. He received an MSc in Mechanical Engineering (2005) from the University of Toledo, USA, and a BS in Mechanical Engineering (2002) from Jawaharlal Nehru Technological University, India. His research activities are in the areas of nanocomposites, reliability and probabilistic analysis, micromechanical modelling, and biobased and biodegradable composites. He has authored/co-authored eight journal articles, six refereed conference proceedings, and a book chapter in "Engineering Design Reliability Applications: For the Aerospace, Automotive and Ship Industries," published by Taylor & Francis.

**George Auer** is currently working towards a BSE in Mechanical Engineering at University of Wisconsin-Milwaukee. He is a member of Tau Beta Pi, an engineering honor society. He plans to continue his studies in either biomedical or materials engineering with an emphasis on tissue engineering and biomaterials.

**Shaoqin Gong** received a BSE and MS degree in Materials Science and Engineering from Tsinghua University in 1991 and 1994, respectively. She received her Ph.D. in Materials Science and Engineering from the University of Michigan-Ann Arbor in 1999. After working for Henkel Corporation as a senior materials scientist for more than three years, she worked as an assistant scientist in the Polymer Engineering Center at the University of Wisconsin-Madison for three years. Since 2005, she has been an Assistant Professor at the University of Wisconsin-Milwaukee in the departments of Mechanical Engineering and Materials Science and Engineering.