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A novel method of producing lightweight microcellular injection molded parts with improved ductility and toughness

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ABSTRACT

This paper presents a novel method and the underlying mechanisms of improving the ductility and toughness of polymer blend components using microcellular injection molding. By producing a special microcellular structure and morphology in polymer blends of proper material formulations, the ductility and toughness of the foamed parts can be significantly improved compared to those of solid parts. The key is to achieve a microcellular structure with a sub-micron scale immiscible secondary phase uniformly dispersed in the primary polymer matrix. Upon tensile loading, cavitation of the secondary phase facilitates the interconnection of microcellular voids to form channels such that the stretched component transforms into a bundle of fibrils. This change in structure turns the fracture mechanism from crack propagation across the matrix into shear yielding of a bundle of fibrils in the loading direction. Process conditions, microstructures, phase morphologies, and mechanical test results of three different types of polymer blends, namely, polypropylene/high-density polyethylene (PP/HDPE), polypropylene/low-density polyethylene (PP/LDPE), and poly(lactic acid)/poly(3-hydroxybutyrate-co-3-hydroxy-valerate) (PLA/PHBV) blends, are presented. Compared with other toughening methods, this method achieved a more significant improvement in ductility and toughness while reducing material consumption and part weight.

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1. Introduction

Since 1976, plastics have been the most widely used materials in the U.S., surpassing steel, copper, and aluminum combined by volume. Among all of the plastics processing methods, injection molding accounts for approximately one-third of all polymer processes [1]. While plastics have become ubiquitous, petroleum resources remain finite, and the cost of fossil-based plastics will continue to increase. Special injection molding processes that reduce material consumption are highly desirable from the viewpoint of not only reducing production and transportation costs but also in the sustainability of natural resources as well as saving the environment. Among various special injection molding processes, microcellular injection molding is capable of producing lightweight, complex parts with a microcellular structure, all while requiring lower injection pressures and energy, shorter cycle times, and less material.

The original concept of microcellular plastics was conceived at MIT in the 1980s by Professor Nam Suh [2]. That approach, which is still used today, employs supercritical fluid (SCF) as a physical blowing agent (PBA) to produce a microcellular structure with an average cell size of 100 μm or less. Later, Trexel Inc. combined the ideas of microcellular plastics with injection molding to develop the microcellular injection molding process (MIM), which is commercially known as the MuCell® process [3]. This process blends SCF (usually nitrogen, N_2, or carbon dioxide, CO_2) with polymer melt in the injection molding machine barrel to create a single-phase polymer–gas solution. During the molding process, the formation of micro cells is triggered by thermodynamic instability via a sudden change of melt pressure as the polymer–gas solution is injected into the cavity through the nozzle. The size of the cells is generally inversely proportional to the cell density, both of which are determined by the thermodynamics of cell nucleation and growth, the amount of gas dissolved in the polymer as well as the polymer itself, the process conditions, the presence of fillers, additives, or a secondary blend phase, and the geometry of the cavity.

The microcellular injection molding process continues to attract attention because it saves on material costs and energy while

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Table 1
Material composition of polymer blends by weight ratios.

PP/HDPE	100/0, 75/25, 50/50, 25/75, 0/100
PP/LDPE	100/0, 75/25, 50/50, 25/75, 0/100
PLA/PHBV	100/0, 90/10, 80/20, 70/30

Table 2
Process conditions used in material blending.

| *For PP/HDPE and PP/LDPE blends*	
Barrel temperature	170/175/180/185/190/195/195/200 °C Hopper<——————————————–>Die
Feed rate	43.7 g/min
Screw speed	150 rpm
For PLA/PHBV blends	
Barrel temperature	165/170/170/175/175/180/180/185 °C Hopper<——————————————–>Die
Feed rate	26.4 g/min
Screw speed	80 rpm

Table 3
Process conditions used in microcellular injection molding.

Nozzle temperature	
PP/HDPE	220 °C
PP/LDPE	220 °C
PLA/PHBV	190 °C
Injection speed	40 cm³/s
Shot volume	20 cm³
Coolant temperature	15 °C
Cooling time	30 s
Gas (N₂) content	0.8%

improving dimensional stability and production efficiency [4]. In addition, the microcellular components offer beneficial properties such as better thermal and acoustic insulation as well as additional degrees of freedom in product design and part thickness variation. Despite the aforementioned processing benefits and part weight reduction, microcellular injection molded parts produced through microcellular injection molding typically exhibit mechanical properties that are inferior to that of solid injection molded parts. This includes ductility and toughness.

A considerable amount of research has been devoted to the development of toughening methods of plastics as well as to the investigation of toughening mechanisms. The most extensively studied and widely applied approach is the incorporation of rubber particles in the polymeric matrix [5–10]. Upon tensile stress, cavitations will occur inside of the rubber particles and/or at the rubber/matrix interface [11,12]. Besides cavitations, the rubber particles may also debond from the matrix [13], effectively reducing the stress required to initiate crazes in the polymer matrix and thus boosting the crazing. Since crazing absorbs a significant amount of energy, the material can be toughened [14]. Shear yielding may also occur, further dissipating the energy and improving the toughness [15,16]. The major drawback of this method, however, is the severe reduction of material stiffness and strength [17–19]. Besides this method, melt blending polymers with flexible and soft thermoplastics has also been proven to increase the toughness [20–22]. In addition, a few studies reported that rigid particles can also be used as toughening modifiers [23,24]. *In-situ* fibrillation using liquid crystal polymers (LCP) [25] as well as thermoplastics such as polyethylene terephthalate (PET) [26] and polyamide 6 (PA6)/ isotactic polypropylene (iPP) [27] have also been proposed as a means of improving toughness.

Recently, it has been found in our experiments that by creating a foamed structure using microcellular injection molding in certain polymer blends, dramatic improvement in part ductility and
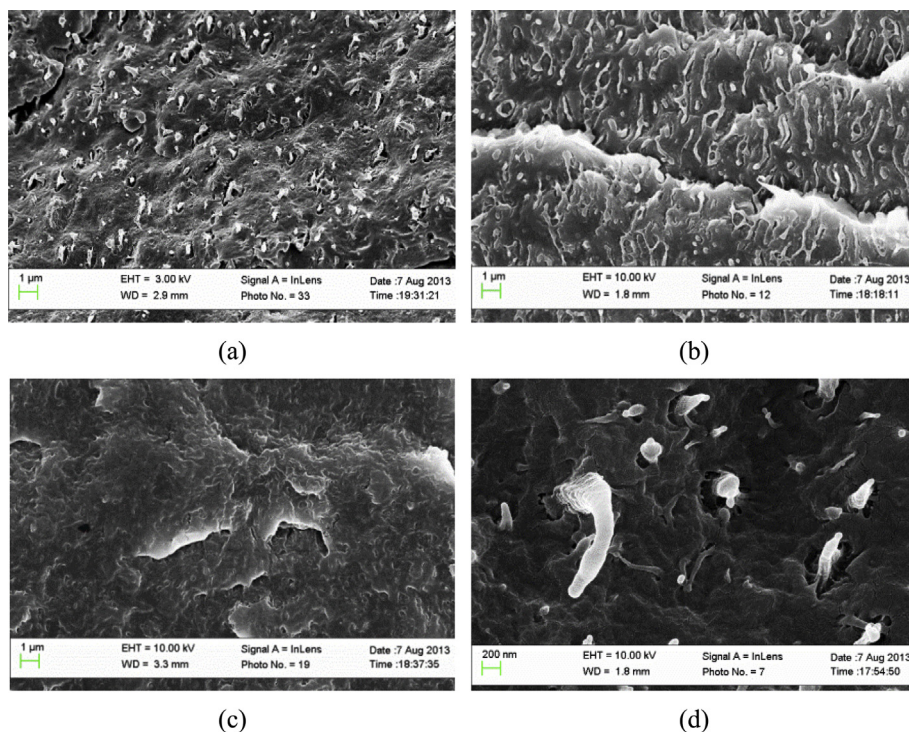
Fig. 1. SEM images of (a) 75/25 PP/HDPE, (b) 50/50 PP/HDPE, (c) 25/75 PP/HDPE, and (d) 75/25 PP/HDPE blends at a greater magnification. Scale bars are 1 μm for (a) through (c) and 200 nm for (d).