Research Letter

Fabrication of super ductile polymeric blends using microcellular injection molding

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Abstract

A novel ductility enhancing method for injection molded plastic parts has been developed. By applying microcellular injection molding to polymer blends of proper morphology, the ductility and toughness of the molded parts can be significantly improved while using less material. The key is to achieve a microcellular structure with a sub-micron scale immiscible secondary phase. Upon tensile loading, debonding of the secondary phase facilitates the interconnection of microcellular voids to form channels such that the stretched component becomes a bundle of fibrils. Compared with other toughening methods, this method achieved a more significant improvement in ductility and toughness.

The cost of fossil-based plastics continues to increase due to the increasing scarcity of petroleum resources. Special polymer processing techniques that reduce material consumption are highly desirable from the viewpoint of not only reducing production costs but also in the sustainability of natural resources and saving the environment.

The microcellular injection molding (MIM) process was developed for this purpose. The concept was conceived at MIT in the 1980s by Professor Nam Suh [1]. This approach, which is still used today, employs supercritical fluid (SCF) as a physical blowing agent and is capable of producing lightweight plastic foams with an average cell size of 100 μm or less [1]. Later, Trexel Inc., combined this concept with injection molding and commercialized this process under the trade name of MuCell® [2]. MIM continues to attract attention because it saves on material costs

and energy while improving dimensional stability and production efficiency [3]. Despite the aforementioned processing benefits and part weight reduction, parts produced through MIM typically exhibit mechanical properties that are inferior to that of the solid injection molded parts. This is especially true for ductility and toughness.

A considerable amount of research has been dedicated 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 [4–9]. Upon tensile stress, cavitations will occur inside of the rubber particles and/or at the rubber/matrix interface [10,11]. Besides cavitations, the rubber particles may also debond from the matrix [12], 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 [13]. Shear yielding may also occur, further dissipating the energy and improving the toughness [14,15]. The major

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drawback of this method, however, is the severe reduction of material stiffness and strength [16–18]. Besides this method, melt blending polymers with flexible and soft thermoplastics has also been proven to increase the toughness [19–21]. In addition, a few studies reported that rigid particles can also be used as toughening modifiers [22,23]. *In-situ* fibrillation using liquid crystal polymers (LCP) [24] as well as thermoplastics such as PET [25] and PTFE [26] have also been proposed as a means of improving toughness.

In this communication, a novel toughening and ductility-enhancing method is proposed, which is capable of fabricating not only tougher but also lighter-weight injection molded parts. It has been recently found that by creating a microcellular foam structure using microcellular injection molding in certain polymer blends, dramatic improvement in part ductility and toughness can be achieved compared with their solid counterparts. Based on this discovery and further research on a host of polymer blends and composites, a ductility enhancing mechanism is proposed in this paper. Microstructures 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 to substantiate the proposed ductility enhancing mechanism.

1. Experimental

1.1. Materials

The resins used in this study were PP (Bassel Pro-fax SR256M), HDPE (Dow 6200 DMDA6200NT7), LDPE (Marlex KN226, Chevron Phillips Chemical Company), PLA (NatureWorks 3001D), and PHBV (Bopol Monsanto 6L600N19). Nitrogen (N_2) was used as the physical blowing agent.

1.2. Processing & characterization

A twin-screw extruder (Leistritz ZSE18HPe) was used to prepare the various blends used in this study. The PP/HDPE and PP/LDPE blends were prepared at weight ratios of: 75/25, 50/50, and 25/75. The PLA/PHBV blends were prepared at 90/10, 80/20, and 70/30 weight ratios. The injection molding machine used in this study was an Arburg Allrounder 320S equipped with an upgraded Trexel Series II SCF dosing system for microcellular injection molding and with 0.6% nitrogen (N_2) as the blowing agent. An ASTM D638 type I tensile test bar mold was used to mold the samples. An injection volume of 20 cm^3 was used to yield an average weight reduction of 10.8%.

Tensile testing was performed on a mechanical testing machine (Instron 5967) according to ASTM D638. The specimens were positioned between static and movable clamps and stretched with a crosshead speed of 500 mm/min.

A 690% strain was the physical limit of the tensile test instrument. Seven samples were used for each tensile test. A JEOL 6500 and a LEO 1530 scanning electron microscope (SEM) were used to observe the foam cell morphology and blend phase dispersion.

2. Results and discussion

2.1. Tensile test results of HDPE/PP blends

Comparisons of the tensile test properties of the solid and foamed PP/HDPE blends, as well as that of the neat polymers, are shown in Figure 1.

As shown in Figure 1(a–c), the PP/HDPE 75/25 foamed blend showed the most dramatic improvement in ductility and toughness by almost 3 fold compared with the solid counterpart. The value of 690% elongation was the physical limit of the tensile test machine, and therefore, the actual values of ductility and toughness are even higher. Figure 1(d) shows an illustrative comparison of the ductility of the HDPE/PP 75/25 foamed part and the solid PP injection molded part. The ductility of the 50/50 PP/HDPE foamed blend also showed improvement to approximately 485%. The 25/75 blend did not show significant increase in ductility.

2.2. Ductility enhancing mechanism

The mechanism explaining the significant improvements in ductility of 75/25 PP/HDPE foamed parts has been investigated. By close examination under the microscope, it was found that after the tensile test, the 75/25 PP/HDPE foamed parts were highly fibrillated along the tensile load direction in the necking region. Figure 2 shows the SEM images of the HDPE/PP foamed part at different elongations.

There are two key factors needed to achieve this highly ductile structure: (a) a microcellular foam structure (cell size typically below 100 μm, as shown in Figure 2); and (b) an immiscible but compatible submicron-size secondary polymeric phase, as shown in Figure 3(a), in which the HDPE phases were below 1 μm in size. Upon loading, the sub-micron phase will debond from the matrix and the cavities will collapse and then interconnect the microscale foam bubbles along the load direction to form channels such that the stretched part eventually became a buddle of fibrils. A schematic of this mechanism is shown in Figure 3(d). This change in structure turned the fracture mechanism from crack propagation across the polymer matrix into shear yielding of a bundle of fibrils being stretched in the tensile load direction. As such, the local stress will be completely relieved and redistributed after the material breaks into fibrils loosely connected laterally and will not propagate across the part. In this way, the ductility of the part can be greatly improved. Such conditions were realized at only the 75/25 PP/HDPE ratio among all of the compositions attempted. The 50/50 blend exhibits a