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Foam injection molding enhances the electrical conductivity of nanocomposites

Amir Ameli, Chul Park, and Petra Pötschke

Adding foam to polypropylene/carbon nanotube composites increases electrical conductivity by more than six orders of magnitude while decreasing density.

Conductive polymer composites (CPCs) have many promising applications in a wide range of fields, including energy storage and conversion, electromagnetic shielding, thermal management, and sensing. Many industries make use of CPCs, including electronics, energy/power, automotive, aerospace, and healthcare. The composites are valued for their superior resistance to chemicals and corrosion, their toughness, and the fact that they are made from inexpensive materials and processing methods. However, CPCs do have drawbacks, such as high filler loading, that not only adversely affect their processability, economic viability, and weight, but also their structural properties.

Numerous research attempts are being made to decrease the filler loading while maintaining a high level of electrical conductivity. Our previous research indicated that some of the challenges associated with CPCs may be tackled effectively using foaming technologies.[1–6] During foaming, the presence of high-pressure gas and the action of bubble growth both affect the microstructure, which can result in reduced filler loading, improved functionality, and decreased weight and cost. Physical foaming during the injection molding process improves the CPCs in several ways. The presence of dissolved gas in the polymer decreases the CPC melt viscosity, thereby easing processing. The decreased viscosity in turn reduces breakage and aids orientation of fillers during injection molding, which helps to lower the required filler loading.[1,2,4] Moreover, polymer stretching exerted by bubble growth (an action similar to inflating a balloon) during foaming alters the fillers' alignment and interconnection around the bubbles, which is highly desirable in some applications (see Figure 1).[1,5,6] Importantly, foaming decreases the overall density by providing a cellular microstructure.[1–6]

In this work, we used polypropylene/multiwalled carbon nanotubes (PP-MWCNTs) as the model nanocomposites. We dry-blended PP-MWCNTs with neat PP to fabricate nanocomposites of various MWCNT content, up to 2.56 vol.%, using a microcellular foam injection machine (see Table 1).[1] We then cut disc-shaped samples from the injection-molded parts in order to measure electrical conductivity.

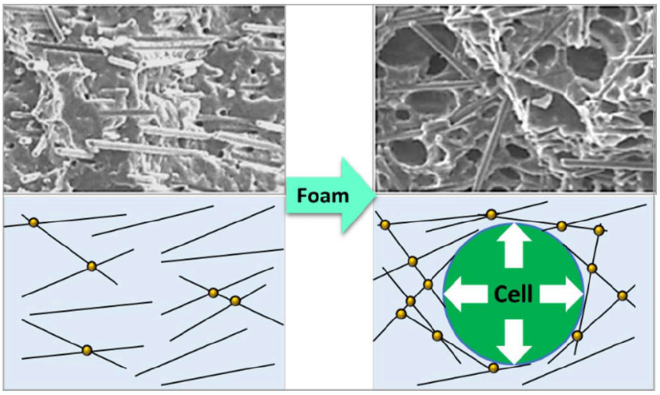

Figure 1. Micrographs of solid and foamed polymer matrix with multi-walled carbon nanotubes (MWCNTs).[2] The nanotubes align and interconnect during foaming.

A solid skin layer formed in both solid and foam samples, characterized by highly oriented fillers in the flow direction (region A): see Figure 2.[2,3,6] In the solid samples, the core was also a solid region, but with a different fracture pattern, indicating that the nanotubes were aligned differently in the skin layer.[2]

In the foam samples, the skin layer was adjacent to a foamed region with elongated cells in the flow direction, called the transition region (region B), while the core was a foamed region with more spherical cells (region C). Different cellular morphologies in the core and transition regions can be attributed to different shear stresses and temperature gradients across the mold thickness.[3]

Solid and foam samples with an MWCNT loading of less 0.64 vol.% had similar conductivity. This did not change with MWCNT

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Table 1. *Processing parameters used in the injection molding of polypropylene/multiwalled carbon nanotube (PP-MWCNT) nanocomposites.*

Parameters	Solid	Foam
Melt temperature (°C)	200	200
Injection flow rate (cm^3/s)	100	100
Barrel pressure (MPa)	16	16
Screw speed (rpm)	500	500
Metering time (s)	9	9
Mold temperature (°C)	30	30
Pack/hold pressure (MPa)	80	N/A
Pack/hold time (s)	5	N/A
N_2 injection pressure (MPa)	N/A	24
Void fraction (%)	N/A	30
N_2 content (wt.%)	N/A	0.3

concentration (see Figure 3). However, beyond 0.64 vol.% MWCNTs, the conductivity began to increase with nanotube content in both solid and foam samples. The rate of increase was significantly higher in the foamed samples, compared with the solid ones, so that the conductivity was six orders of magnitude higher at 2.56 vol.% MWCNTs.

Physical foaming during injection molding improves electrical conductivity by reducing the polymer melt viscosity and increasing polymer stretching. The lower viscosity resulted in less breakage and a nanotube orientation that contributed to the effectiveness of the percolation network.[2,3,5] The stretched polymer also disrupted the in-plane orientation of nanotubes via three-dimensional growth of cells. This improved their interconnectivity and translated into a higher electrical conductivity.

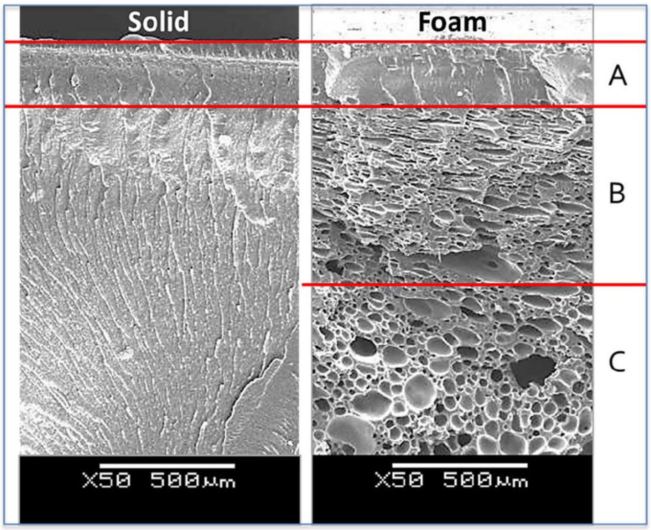

Figure 2. *Microstructure of the solid and foam PP-MWCNT nanocomposites. Region A has highly oriented nanotubes, region B is a transition region, and region C is the core.*

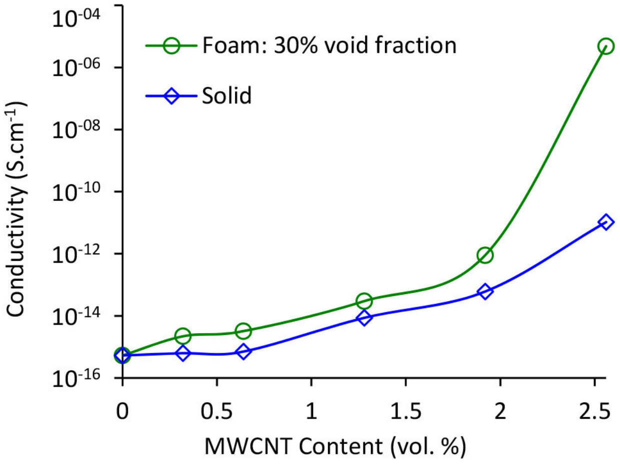

Figure 3. *Electrical conductivity of solid and foam injection-molded PP-MWCNTs as a function of MWCNT content.*

In summary, our work shows that the physical foaming of polymer nanocomposites in injection molding contributes to weight reduction as well as enhancing electrical conductivity. This represents a significant step toward more lightweight, cost-effective, and high-performance products. Without having to increase the filler loading, we can increase electrical conductivity by six orders of magnitude and reduce weight by 30%. In future, we plan to optimize our foaming technologies to yield further improved results and also to develop conductive foam products for specific applications such as charge storage, electromagnetic shielding, and electrostatic dissipation.

Author Information

Amir Ameli
Washington State University
Richland, WA

Amir Ameli directs the Advanced Composites Laboratory in the Mechanical and Materials Engineering Department.

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Chul Park
University of Toronto
Toronto, Canada

Chul Park holds a Tier 1 Canada research chair in microcellular plastics at the University of Toronto. He is founder and director of the Microcellular Plastics Manufacturing Laboratory and the Centre for Industrial Application of Microcellular Plastics.

Petra Pötschke
Leibniz Institute of Polymer Research Dresden (IPF)
Dresden, Germany

Petra Pötschke heads IPF's Department of Functional Nanocomposites and Blends.

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