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Foam injection molding with nitrogen and carbon dioxide as co-blowing agents

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A novel process combines gas-laden pellets and microcellular injection molding to produce thermoplastic polyurethane foams with low density, uniform cell structure, and high durability.

Low-density thermoplastic polyurethane (TPU) foam is used widely today in furniture, automotive, sportswear, and packaging applications because of its advantageous properties. Such properties include its light weight, as well as its good cushioning effect, fast energy restoration under compression, and high wear resistance. To date, most TPU foams have been produced by either batch foaming[1,2] or extrusion foaming[3,4] techniques. Batch foaming processes, however, suffer from an intrinsically low production rate, and foam extrusion imposes limitations on the design of part geometries.

Foam injection molding can be used to effectively overcome the two limitations associated with batch and extrusion foaming. Microcellular injection molding (MIM)—developed and commercialized by Trexel, under the trade name MuCell[5]—is one of the most widely used foam injection molding techniques. During the plasticizing process of MIM, a supercritical fluid (SCF) is injected and mixed into the polymer melt and the mixture is then injected into the mold cavity. The sudden pressure drop induces thermodynamic instability, which causes the dissolved gas to nucleate and form a microcellular foam structure inside the molded part.

In our work we have invented an alternative foam injection molding approach that is known as the supercritical fluid-laden pellet injection molding foaming technology (SIFT).[6] Instead of injecting the SCF directly into the injection molding barrel, in our technique the SCF is first embedded into plastic pellets through a special extrusion process. We then use conventional machines to injection mold these gas-laden pellets into a foam part. With our SIFT method, we can produce gas-laden pellets with only one extruder that is equipped with a gas injection device. As such, modifications and device additions are only required for one extruder. Furthermore, the gas-laden pellets can be used in several different conventional injection molding machines—without requiring any modification or additional equipment—to produce lightweight foamed parts. In this way, we are able to significantly reduce the equipment costs, as well as the amount of work required for machine modifications, associated with injection molding. Full details of our technology have previously been published.[6,7]

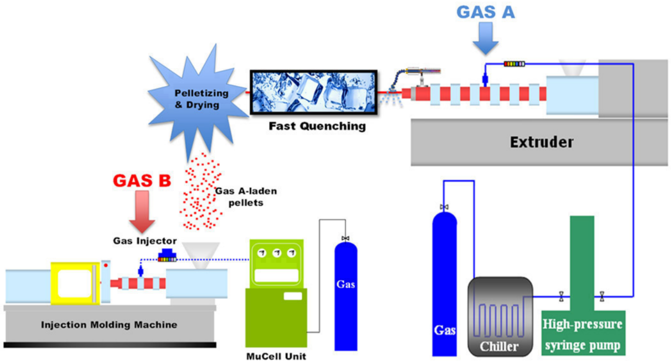

Figure 1. *Schematic diagram of the combined supercritical fluid-laden pellet injection molding foaming technology (SIFT)/microcellular injection molding (MIM) process.*

In one of our earlier studies,[7] we found that combining nitrogen (N_2) and carbon dioxide (CO_2) in appropriate ratios as co-blowing agents creates a synergetic effect. This induces stronger cell nucleation than either of these two components can produce individually. A finer cell structure is thus created, as well as further weight reductions. In this work, we have investigated a novel SIFT/MIM combination scheme (see Figure 1). By combining these two processes, the dosage of the two different blowing agents can be controlled independently. In this methodology, we embed the first blowing agent into the gas-laden pellets before the second blowing agent is injected during the MIM process.

We conducted a four-factor three-level design of experiments (DOE) to identify significant factors and define the process window for our

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methodology (see Table 1). Our input factors included the CO_2 content in the gas-laden pellets (we maintained the N_2 content at 0.8%), mold temperature, injection volume, and cooling time. The DOE covers three levels of value for each input factor, which are shown in Table 1. The output variables from the DOE that we evaluated included the cell nucleation density, bulk density, compression hysteresis loss, Shore A hardness, and tensile strength.

Table 1. *Details of the four-factor three-level design of experiments (DOE) setup. Numbers inside the parentheses indicate the values of the input factors used in each run. Numbers outside the parentheses refer to their levels in the DOE. CO_2: Carbon dioxide.*

Trial	SIFT CO_2 content (%)	Mold temperature (°C)	Injection volume (cm^3)	Cooling time (s)
1	1 (0)	1 (60)	1 (17.5)	1 (40)
2	1 (0)	2 (65)	2 (18.0)	2 (45)
3	1 (0)	3 (70)	3 (18.5)	3 (50)
4	2 (0.5)	1 (60)	2 (18.0)	3 (50)
5	2 (0.5)	2 (65)	3 (18.5)	1 (40)
6	2 (0.5)	3 (70)	1 (17.5)	2 (45)
7	3 (0.8)	1 (60)	3 (18.5)	2 (45)
8	3 (0.8)	2 (65)	1 (17.5)	3 (50)
9	3 (0.8)	3 (70)	2 (18.0)	1 (40)

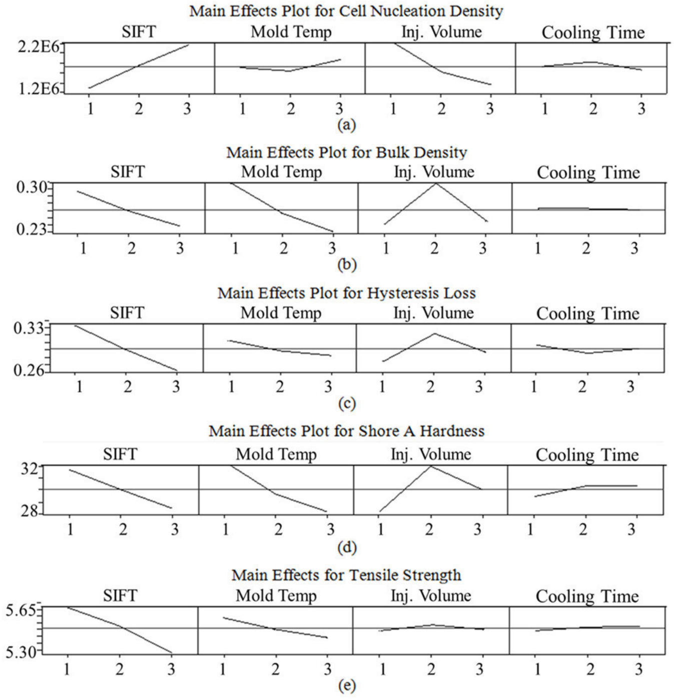

Figure 2. *Plots illustrating the main effects of the DOE (see Table 1).*

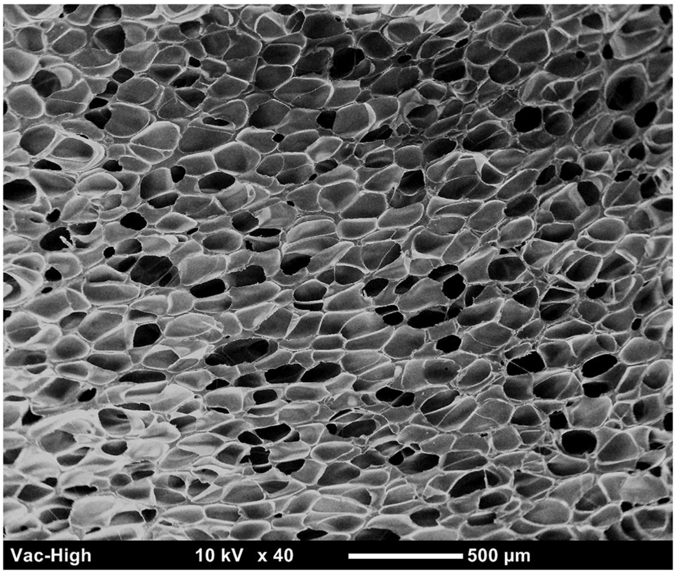

Figure 3. *Scanning electron microscope image showing the morphology of the cell structure produced during trial 8 (see Table 1) of the experiments.*

The main effects of the four input factors over the five output factors are shown in Figure 2. We find that by incorporating CO_2 into the gas-laden pellets, in combination with N_2, an improved foam quality is achieved. By using a higher CO_2 content, we can produce a lower bulk density foam with a finer cell structure. Meanwhile, a reduced hysteresis loss improves the durability of the part that is under cyclic compression. Overall, our results indicate that it is preferable to have a higher mold temperature and moderate injection volume. From all our tests, we find that trial 8 (see Table 1) exhibited the optimal properties. With this trial we produced the lowest bulk density ($0.2g/cm^3$) and the lowest hysteresis loss (24.4%). We can thus ensure a high level of energy restoration and long-lasting performance under long-term cyclic loading. A scanning electron image of the cell structure produced during trial 8 is shown in Figure 3.

In this study, we have successfully produced highly expanded TPU foams with the use of a novel gas-laden pellet/MIM combined process. We have also conducted a DOE to investigate the influence of various processing parameters. We use CO_2 and N_2 as the co-blowing agents in our SIFT/MIM combined process, and we are therefore able to achieve a further reduction in the bulk density and hysteresis loss. As a general process guideline, we find that higher gas content, higher mold

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temperatures, shorter cooling times, and moderate injection volumes are preferred for producing low-density TPU foam injection molded parts. The next stage in our work is to investigate the feasibility of our method for other thermoplastic materials. We will conduct more detailed studies and hope to report these results in the future.

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