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Open-cell cavity-integrated injection-molded acoustic polypropylene foams

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ABSTRACT

In this study, a commercially available foam injection-molding machine was enhanced with a mold opening technique to produce polypropylene open-cell acoustic foams. Gas counter-pressure was used to improve the cell morphology and uniformity of the injection-molded foams. Their structure and thickness were controlled by applying different degrees of mold opening. The sample structure, the cell morphology, and the acoustic behavior of the foams were characterized. A foamed structure with an open-cell content of 67% and an expansion ratio of 4.6 was obtained when the mold was opened by 4.5 mm. Although further opening of the mold did not significantly increase the open-cell content, it triggered crack creation in the middle of the foams, where the creation of cavities was also facilitated. The injection-molded foams with a cavity and a high open-cell content, presented remarkable acoustic properties: a peak absorption coefficient of 0.95 was observed for foam with a 73% open-cell content and a 9 mm cavity. An automated system was also developed to perforate the acoustic foams, and the acoustic properties of foams both with and without perforation were studied. While perforating the foams widened their absorption coefficient frequency spectrum, it did not improve their transmission loss.

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1. Introduction

Unfortunately, most noise control materials currently available are not environmentally- friendly or recyclable. Polyurethane foams are commonly used as sound insulators [1–3]. But it is difficult to treat polyurethane foam waste. These foams are not easy to recycle cost-effectively and their incineration produces poisonous gas [4,5]. Their low density and high volume means they easily become landfill. Glass wool has also been used as a sound insulator but only in a rough (non-human) environment due to health concerns. Also, fiberglass was not considered a reliable acoustic controller due to its relatively high density and low processability [6]. Therefore, thermoplastic materials such as polypropylene would be a promising alternative to the currently available sound insulating materials [7].

Open-cell foams have shown promise for sound insulation across a wide range of frequencies [8,9]. The interconnectivity of their cells allows air particles to flow through them. Air-flow viscosity and the thermal conductivity of the foam are considered as the two main reasons for sound wave attenuation [10]. Nevertheless, to absorb low-frequency sound with conventional open-cell foams, a considerable foam thickness is required [11]. Multilayer acoustic foams [12,13] constructed with a front panel, open-cell foam, and an air–gap promise to provide alternative solutions for low-frequency sound absorption (400–1600 Hz). In some applications, the front panels were perforated to enhance their acoustic behavior [14,15]. The costs associated with multilayer acoustic foams are relatively high and, in most cases, the open-cell foams used in such insulators are not recyclable. It is thus of great value to develop cost-effective and recyclable alternatives to these resonators.

Several strategies have been examined to produce thermoplastic open-cell foam materials. A batch foaming process coupled with a salt leaching method to fabricate open-cell foams was studied [16,17]. In the salt-leaching method, it is easy to control the cell size; however, the cost associated with this method is relatively high. During a batch foaming process, Kohlhoff and Ohshima recently produced a polylactide-based open-cell foam by blending amorphous polylactide with polystyrene [10]. Lee et al. produced high open-cell content foams using different strategies in extrusion foaming. This included using two semicrystalline polymers with different crystallization temperatures [18], plasticizing soft regions with a secondary blowing agent [19], using a non-homogeneous melt structure [20], and maintaining a high temperature difference between the surface and the core of the foam extrudate [21].

The manufacture of open-cell foams using the foam injection-molding process is of great interest to industry. This is due to its reliability, availability and cost-effectiveness. Producing open-cell injection-molded foams is, however, challenging and has received

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very little attention. Since foaming takes place in an enclosed mold cavity, the range of achievable void fractions and cell densities is limited in the foam injection-molding process [22,23]. Therefore, foam injection-molding strategies should be developed in order to be able to achieve highly expanded open-cell foams.

In this study, the conventional foam injection-molding process was equipped with mold opening and gas counter-pressure techniques [23,24]. It successfully produced relatively low-density open-cell foams and created air–gap integrated acoustic foams. A mechanized perforating apparatus was also developed to assess the effects of perforation on the structure's acoustic behavior. The sample structure, cell morphology, and acoustic behavior of the foams were then thoroughly investigated.

2. Experimentation

2.1. Preparation of acoustic foam samples using injection-molding

To achieve an effective acoustic foam using the injection-molding process, the three requirements should be met: (i) capability to produce foams with relatively high void fractions; (ii) to interconnect the cells to increase the open-cell content; and (iii) to create cavity inside the foams to enhance their acoustic behavior. The opening of the mold enabled the melt to flow one-dimensionally in the sample thickness direction, causing the cells to grow further in that direction and to experience additional shear and extensional stresses. The temperature of the polymer melt was tuned to obtain optimum melt strength and thus enhanced the cell growth capacity while preventing the cells from collapsing [25,26]. Excessive cell growth resulted in extremely thin cell walls and thus pinholes on the cell walls could be created as a result of the induced biaxial stretching from expansion and polymer shrinkage of the thin walls during the solidification [26,27]. Especially, the low melt strength of linear polypropylene used in our study can cause cell wall rupturing and opening easily [28]. After the cells were expanded and solidified, a further opening of the mold in a timely manner initiated a crack in the foam core as a result of residual stress on the foam. Eventually, an opening in the mold caused a full-length crack in the foam core and a cavity was developed in the middle of the foam. The mold was kept cold (i.e., at room temperature) to enable rapid solidification of the foam and to create a residual stress in the foam core. The length of the mold opening was adjusted to produce a foamed structure without a cavity and also cavity-integrated acoustic foams of different thicknesses.

The commercially available injection-molding grade of polypropylene (PP), Certene PHM35 was used. It was provided in a pellet form and had a specific gravity of 0.903 g/cm^{-3}, a melt flow index of 35 g/min, and a Vicat softening temperature of 152 °C. Nitrogen (N_2) was supplied by Linde Gas, Canada and used as the physical blowing agent. A 50-ton Arburg Allrounder 270/320 C injection-molding machine (Lossburg, Germany), with a 30-mm diameter screw equipped with MuCell® technology (Trexel, Inc., Woburn, Massachusetts), and a gas counter-pressure module (Caropreso Associates, MA, US) were used to conduct the injection-molding experiments. The mold contained a rectangular cavity with a fan gate at one end. The cavity dimensions were 135 mm × 111 mm × 3.2 mm. More details about the mold can be found in [29,30]. The mold cavity was first pressurized at about 6 MPa, and then the polymer/gas mixture was injected into it while the gas counter-pressure was maintained to avoid premature cell nucleation and growth during filling. The mold cavity was filled partially by injection (i.e., 75% of the full shot) and foaming was induced later by releasing the gas from the mold cavity and mold opening. Fig. 1a shows the sequences of the steps for a full injection cycle and the level of the desired cavity pressures. As Fig. 1b shows, mold cavity pressures were also measured at three different locations: near the gate, the middle of the cavity, and near the end of the cavity for the entire injection cycle using three PT462E Dynisco pressure transducers and a DAQ board (Compact DAQ Kit, National Instruments) to ensure that the desired pressures were achieved at each phase of the entire process.

Table 1 summarizes the fixed and varied foam injection-molding parameters. The optimum values for the fixed parameters were first determined by a series of trial and error experiments. With a short delay (about 2s) after the polymer melt was injected into the cavity, the mold was opened enabling the cells to grow. An optimized delay was intended to allow the skin of the injection-molded part to be solidified before opening the mold to maintain structural integrity. Avoiding or shortening the delay time resulted in non-flatness of the skin of the injection-molded parts. Longer delays produced a thicker solidified skin, which was not suitable for obtaining high expansion ratio foams and creating foam cavities.

The polymer melt was injected into the cavity at the maximum capacity of the injection-molding machine for a flow rate of 100 cc/s throughout the process. A high flow rate resulted in a high shear rate, and consequently, the cells were elongated in the flow direction. The degree of mold opening was determined as the most influential parameter on the final structure of the expanded samples and thus varied to investigate its effects on the overall structure, the foam morphology and the acoustic behavior of the injection-molded samples. Other parameters were kept unchanged in all of the experiments.

2.2. Foam characterization

The foam density (ρ_f) was measured using the water-displacement method (ASTM: D792-08), and the relative density (ρ_N) or expansion ratio was calculated as the ratio of the measured density of the foam sample (ρ_f) and the density of the corresponding unfoamed material (ρ_s). To measure cell size and density, the samples were freeze-fractured and then coated with platinum using a sputter coater. The microstructures were then examined using a scanning electron microscope (SEM), JEOL JSM-6060. The image processing was carried out using ImageJ software, developed by the National Institutes of Health, US. The cell density was calculated from a micrograph and using the equation

$$\text{cell density} = \frac{\frac{nM^2}{A}}{\rho_N} \tag{1}$$

where n is the number of voids in the micrograph, A is the area of the micrograph, and M is the magnification factor of the micrograph. The open-cell content of foams was measured using a gas pycnometer (Quantachrome Instrument UltraFoam 1000) in accordance with the ASTM: D6226-10.

2.3. Perforation

Fig. 2 shows the developed mechanized perforating apparatus used with injection-molded foams. An oven was heated by an embedded electrical element, which was connected to a programmable temperature controller (TC). The perforator was rotated by a DC motor equipped with a rotational speed controller. The oven was heated to the melt temperature of the polymer, and the sample was placed between the roller and the mechanical perforator. The proper perforation of the samples was carried out by tuning the rotational speed, the temperature and the gap between the roller and the perforator by nub screws.

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