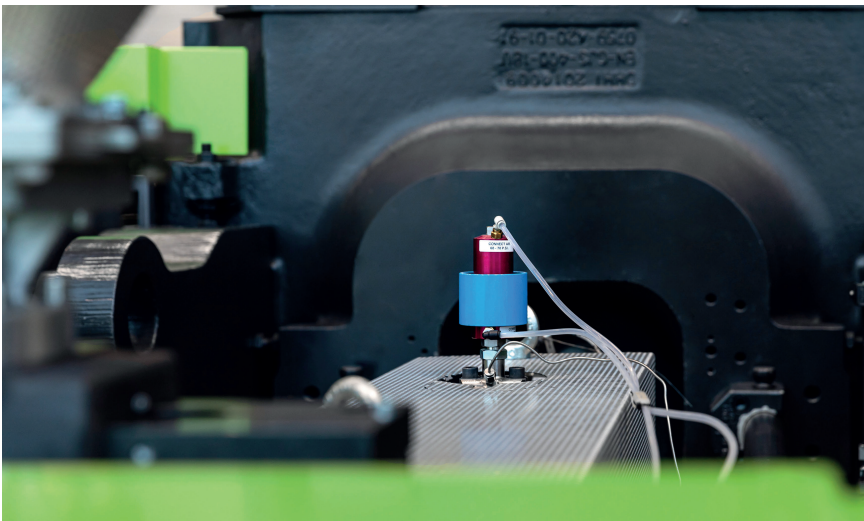


A Special Process that Is Becoming a Sustainable Normal Case

New Developments in Thermoplastic Foam Injection Molding

Lightweight parts, energy-saving processing or the practice of combining several process steps into one can all be subsumed under one current buzzword: sustainability. A technology that is highly promising in this regard is thermoplastic foam injection molding. Although in use for decades, the process offers great potential thanks to continuous development work.



In physical foam injection molding, a blowing gas is injected into the polymer melt during plasticizing © Engel

The thermoplastic foam injection molding (TFIM) offered by Engel Austria GmbH, Schwertberg, Austria, under the name foammelt is one of the oldest special injection molding processes. The commercialization, principally of chemical TFIM processes at first, began in the 1950s. Small amounts of baking powder were added to the melt to avoid sink marks in the part [1]. Chemical blowing agents grew in importance and led to the first series production of foamed parts in the 1970s [2].

The use of supercritical fluids (mainly nitrogen and carbon dioxide, **Title figure**) in physical TFIM processes, such as MuCell (supplier: Trexel GmbH) today permits the manufacturer of microcellular foams with pore diameters below 100 μm or cell densities of over 10^9 cells/cm³. This special morphology offers advantages particularly for impact applications, since the

fine cells act as crack arrestors [3]. Although the foaming of polyolefins during injection molding has undergone many years of development, many questions remain open. Current developments, such as those pursued by the Institute of Polymer Injection Molding and Process Automation (IPIM) at the Johannes Kepler University of Linz, Austria, together with Engel, as well as the Competence Center Chase GmbH, are aimed at finding alternatives to gas introduction, investigating the conditions in the plasticizing unit, as well as the deployment of Industry 4.0 technologies.

Minimized Warpage, Improved Shape Accuracy

Foamed parts have a three-layer structure. A porous core is surrounded by two

unfoamed surface layers. This structure offers advantages, since the material and resource consumption is reduced and a lower density is made possible. Classical density reductions in the TFIM process are around 10%, as new developments in the tool and process technology permit (local) density reductions of up to 50% [4], which underlines the lightweight construction potential of this technology. Another advantage for sustainability is the recyclability of the lightweight components, since the sandwich structure consists of a single material.

As regards the mechanical performance of foamed parts, it is important to note the higher geometrical moment of inertia compared to unfoamed parts and thus the increased specific flexural strength, as a result of the greater distance of the unfoamed outer layer from the neutral fibers. The crack-stopping properties improve the impact behavior of foamed parts [5]. Besides mechanical improvements, these parts also offer inherent functions such as acoustic or thermal insulation without further processing steps.

Technically, the homogeneous gas pressure prevailing during forming of the part minimizes warpage and therefore improves the shape accuracy. In addition, the gases act as plasticizers during processing. Depending on the gas and concentration, the viscosity of the material is reduced by up to 50%, which under certain circumstances permits smaller machines to be used. Primarily, this has an environmental benefit, which makes foam injection molding even more popular, particularly in view of current developments in energy policy.

Exploiting Potential with High Efficiency

By contrast, there are also challenges that stand in the way of TFIM breaking through as a mass production technology. These include the increased machine and technical effort due to the gas introduction into the polymer melt, the tool movements during forming of the part (core back technology) or the complex control of the pressures during dosing. On the other hand, the surface quality of the foamed parts is also important. Due to the pressure drop towards the melt front, the first bubbles already occur in this area during injection. The fountain flow leads to the bubbles being conveyed against the cold tool wall, where they are sheared – this effect becomes visible as silver streaks. Methods for avoiding surface defects, such as variotherm mold temperature control or gas counterpressure, are associated with higher costs and greater technical effort.

To completely exhaust the potential of foam injection molding with high efficiency, it is necessary to understand the fundamentals of the technology even better – especially as regards specific applications – and to develop and test new process technologies. This is precisely the area where the IPIM, the Competence Center Chase, which is also based in Linz, and Engel are working.

The focuses of the joint development work include, for example, the question of how the gas is introduced into the polymer melt and dissolved in it. The gas serving as blowing agent is either added physically in pure form or produced chemically directly in the polymer melt as the thermal decomposition product of a masterbatch. To obtain a homogeneous, single-phase solution, the gas must be mixed into the melt in a very short time. Engel has therefore developed a special plasticizing screw that meets the requirements of physical foam injection molding (Fig. 1).

Own-Developed Plasticizing Screw

The PFS (physical foaming screw) has a shear section, which homogenizes the polymer melt very effectively before the gas is introduced, with a positive effect on uniform gas distribution. In addition, the screw geometry permits the second non-

return valve to be eliminated. In conjunction with a new material execution, which offers an improved abrasion and corrosion resistance, the special geometry increases both the productivity and the durability of the screw.

New Method for Determining the Solubility Limit

The amount of gas that a polymer melt can absorb under certain process conditions is described by the solubility. Many methods exist for describing solubilities under static conditions. The prevailing method is to use so-called magnetic suspension balances, which have a pressure chamber for gas injection in combination with a magnetically coupled balance located outside the pressure chamber.

It can be questioned how relevant such statically determined data are for highly dynamic foam injection molding processes, since any form of movement, in particular of shear processes, is neglected. In addition, static solubility measurements have measurement times of the order of hours, while injection molding processes only permit seconds up to a few minutes at most to absorb the gas into the polymer melt. The scientific literature paints an uneven picture where the influence of shear on the gas solubility is involved. While some authors assume that shear motions do not influence the solubility [6], others report an increase of solubility of up to 40% [7].

Because of this discrepancy, the IPIM has developed a new measurement method that describes the gas solubility under dynamic conditions – inline during the injection molding process. The starting point for the theoretical preliminary



Fig. 1. The geometry of the PFS improves the homogeneity of the gas-containing melt © Engel

work was the Sanchez-Lacombe equation of state (1) for describing the pvT behavior [8] and consequently the bulk modulus K of polymer-gas mixtures (2):

$$\tilde{\rho}^2 + \tilde{P} + \tilde{T} \left[\ln(1 - \tilde{\rho}) + \left(1 - \frac{1}{r}\right) \tilde{\rho} \right] = 0 \quad (1)$$

$$K = - \frac{\Delta p}{\Delta V} V_0 \quad (2)$$

With increasing gas content in the melt, there is a reduction in the bulk modulus of the mixture (Fig. 2). However, a possible solubility limit – the static solubility of nitrogen in polypropylene is 2 to 4%, depending on the pressure and temperature [9] – cannot be described.

For this reason, tests were performed on an injection-molding machine. The bulk modulus characterizes the volume changes as a result of a pressure rise. This state can also be produced in front of the screw tip by leaving a shut-off nozzle closed at the beginning of the injection process in order to compress the material. The pressure rise and volume contraction can be registered by the internal sensors in the machine and evaluated. »

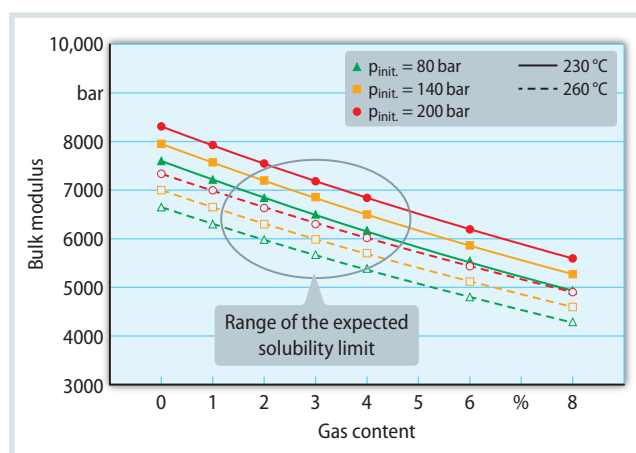


Fig. 2. Result of the theoretical preparatory work: with increasing gas content in the polymer melt, there is a reduction in the bulk modulus of the mixture. A possible solubility limit cannot be described

Source: JKU; graphic:

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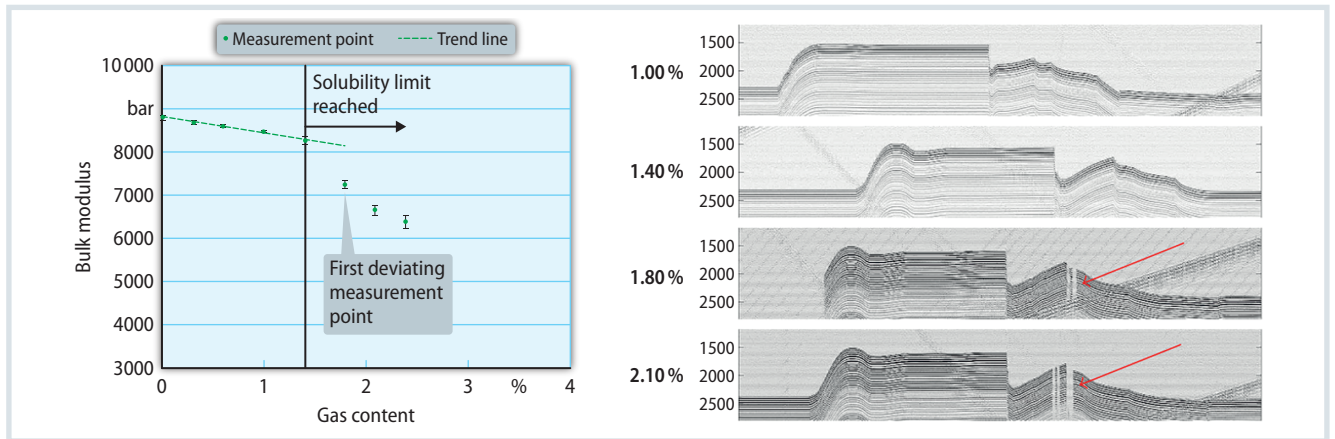


Fig. 3. Example of a bulk modulus measurement: the deflection in the curve (left picture) indicates that a solubility limit has been reached.

Right: ultrasound measurements during injection for verification Source: JKU; graphic: © Hanser

The following mental steps can be described here: gases have a bulk modulus that is lower by about a factor of 10 than that of polymer melts. As long as the gas can be dissolved in the melt, it moderately reduces the bulk modulus of the mixture. Once the solubility limit is exceeded, the gas forms a separate – and far more compressible – phase, which should cause the bulk modulus of the mixture to drop dramatically. It was therefore expected that there would be a deflection in the compression module when the solubility limit was reached.

Measurements on the machine confirmed this behavior (Fig. 3). For verification: interruptions in the ultrasound signal at high gas contents are an indication of undissolved gas bubbles. A new, very process-related measure-

ment method for determining the solubility limit based on the compression behavior was born.

A Widespread Misconception

The latest findings based on this measurement method shatter a widespread misconception. In the course of measuring the solubility limit with nitrogen and carbon dioxide on the injection-molding machine, it could be shown that the gases are not completely dissolved in the polymer melt, but for the most part are only finely divided. In the very short interaction time between melt and gas mentioned above, the function of the intensive shear is thus to produce a polymer-gas mixture that is as homogeneous as possible [10].

By means of the bulk-modulus method, not only material characterizations but also process optimizations are possible. It is particularly economically interesting to automatically reduce the backpressure to the technically necessary minimum, which significantly reduces the wear and energy consumption and improves the conveying behavior. This development is based on the circumstance that gases do not dissolve in the material when the pressures are too low, and consequently form a separate phase. When the bulk modulus is plotted against backpressure with constant gas loading, a knee in the curve is expected again, which is indeed seen in the experiment. This method is also confirmed by ultrasound measurements (Fig. 4). The bulk modulus has therefore proved to be

Thermoplastic Foam Injection Molding since 1914

Thermoplastic foam injection molding is based on methods that were originally developed outside injection molding. The first foamed polymer-based products came onto the market in 1914 [11] and were made of natural rubber. Ammonium carbonate was widely used, which, when an acid was added, released the gases that enabled foaming. In the following two decades the two processes still used today were developed: Dunlop and Talalay. Dunlop is based on the physical mixing of air into the polymer melt together with a gelling agent (often sodium hexafluorosilicate). Talalay uses oxygen as a decomposition product of hydrogen peroxide [12], and is comparable with modern chemical foam injection processes as regards both the foaming mechanism and the discontinuous process control.

Foamed polystyrene represents a milestone. The first patent on this, by Carl Georg Munters and John Gudbrand Tandberg, dates from 1932 [13]. In 1947, the Dow Chemical Company followed suit with an

extrusion process. A mixture of polystyrene, nucleating agent and volatile liquid blowing agents permitted the manufacture of larger foamed parts. The material is now protected under the name Styrofoam. Just four years later, BASF developed a process for manufacturing expandable polystyrene particles (EPS), in which the blowing agent is added already during polymerization.

The foaming of polyolefins took another decade. Here, too, the gases were added to the polymer melt at the beginning. In 1941, Frederick L. Johnston patented two different processes [14]. In the first, nitrogen is dissolved in a polyethylene melt in a pressure chamber while in the second, thermal decomposition of a blowing agent is used. Both processes already have a strong similarity to the physical and chemical processes that are used today in injection molding, although another four years would pass until carbon dioxide was used [15].

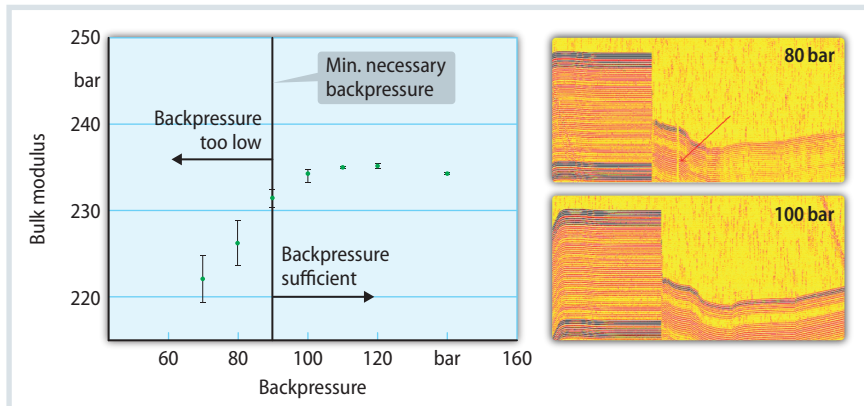


Fig. 4. Use of the bulk modulus method for backpressure reduction when using 0.6% nitrogen: in the left-hand image, the decrease of bulk modulus when the backpressures are too low can be seen. Right: ultrasound measurements during injection for verification Source: JKU; graphic: © Hanser

an important tool for process optimization and for gaining a better understanding of the process in foam technology.

In the future, the injection molding machine will be able to automatically determine and set the minimum necessary backpressure. The intelligent assistant is already an important topic in thermoplastic foam injection molding. “iQ weight control,” which is already successfully used in many chemical and physical foammelt and MuCell foam injection molding processes, achieves better process stability and a constant part weight. The software from Engel’s “inject 4.0” program adjusts the injection profile and changeover point to the current conditions shot for shot during injection molding, and thereby fully automatically compensates external influences such as batch fluctuations and changes of environmental conditions in real time.

Foaming with Artificial Intelligence

Artificial intelligence (AI) opens up even greater potential for optimizing foam processes. Specifically, the three development partners are working on the use of convolutional neural networks for optimizing part surfaces in TFIM processes. The goal is to find optimized process settings for unknown processes without having to perform complicated test series.

In its present form, the convolutional neural network (CNN) developed and trained at the IPIM (Fig. 5) can assign process settings to the parts and thereby make recommendations for parameter adjustments. In future, the scanning of the part will be automated using an autonomous optimization mechanism. In correlation with the setting parameters, the system will automatically correct for deviations from the intended process.

The wide variety of developments at the process, software and machine sides

achieve important steps toward modern foam technology fully exploiting the sustainability potential. In this way, TFIM is less and less to be considered as a special process. ■

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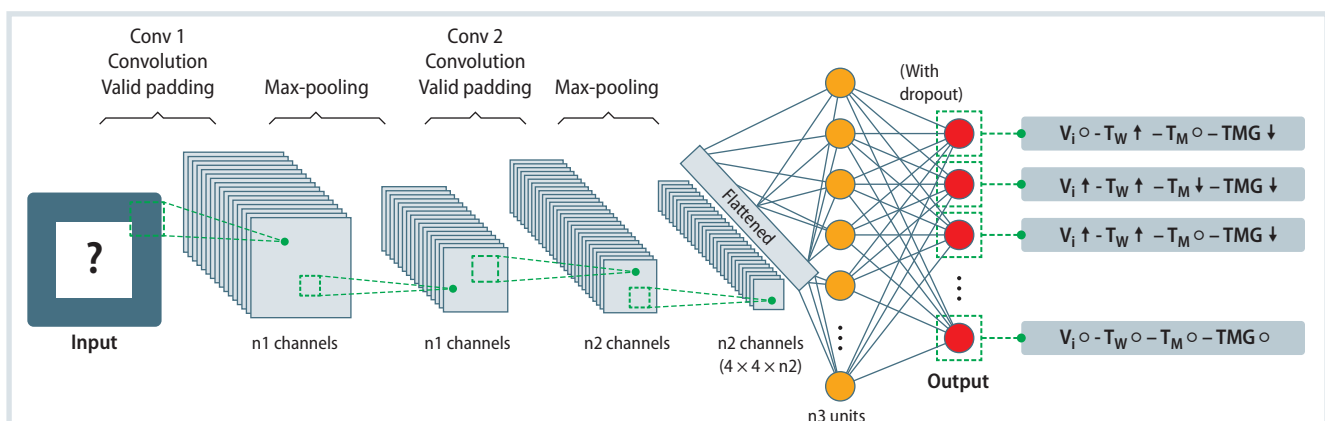


Fig. 5. Artificial intelligence is making inroads into foam injection molding: schematic view of the convolutional neural network and its output for parameter adjustment Source: JKU; graphic: © Hanser