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INTRODUCTION

1.1 HISTORY OF MICROCELLULAR PLASTICS

Historically, microcellular plastics are not new: They existed more or less in the thin transition layer of structural foams. It can be found partially in sections with thin thickness, as well in the high shearing zone of structural foam parts. However, as an idea to develop microcellular plastics, Dr. Nam Suh and his students at the Massachusetts Institute of Technology invented microcellular processing in the early 1980s. This technology proposes two goals: One is to reduce the material, and another is to promote the material toughness by tiny spherical cells that act as crack arrestors by blunting the crack tip [1]. Furthermore, the rigidity of the material in resisting the buckling of the cell walls has been improved through the formation of spherical closed cells. Concentrated research and development efforts of microcellular foams began in the late 1980s, with a focus on the batch process and the topics mentioned above.

The microcellular batch processing technology was invented at the Massachusetts Institute of Technology (MIT) from 1980 to 1984 [1], and the first U.S. patent on microcellular technology was issued in 1984 [2]. Jonathan Colton showed a heterogeneous nucleation mechanism from the effects of additives in the polymers at certain levels of solubility [3]. Jonathan Colton also investigated the methodology of foaming for semicrystalline polymers such as polypropylene (PP) [4]. The gas can be dissolved into the amorphous

Microcellular Injection Molding, Edited by Jingyi Xu

structure because raising the temperature beyond its melting point eliminates the crystalline phase of PP. This heterogeneous nucleation is now dominating today's industry processing. On the other hand, the crystalline material, such as PP, has been used for microcellular foam by Jonathan's method in the industry practice now. Chul Park and Dan Baldwin studied the continuous extrusion of microcellular foam. Chul Park investigated both (a) the dissolution of gas at the acceptable production rate and (b) the application of a rapid pressure drop nozzle as the nucleation device [5]. Dan Baldwin studied the microcellular structure in both crystalline and amorphous materials [6]. Sung Cha investigated the application of supercritical fluid, such as CO_2, to dissolve the gas faster and to create more cells [7, 8]. With supercritical fluid, the cell density was increased from 10^9 cells/cm^3 to 10^{15} cells/cm^3. Vipin Kumar also used thermoforming supersaturated plastic sheets to study the issues of shaping three-dimensional parts [9]. Sung Cha also found that the large volume of gas in polymers decreases significantly with the glass transition temperature of plastics. Therefore, simultaneous room temperature foaming is possible. All of these pioneer contributions are fundamental to microcellular foam technologies. Through many people's creative research, this technology has completed the laboratory stage and transitioned to industry application.

The commercial application of microcellular technology began in 1995 by Axiomatics Corp., which was later renamed Trexel Inc. Trexel continued to develop microcellular technology through extrusion first. Then, the first injection molding machine with plunger for injection and extruding screw for plasticizing and gas dosing was developed in Trexel Inc. with the help from Engel Canada in mid-1997. After successful microcellular injection molding trials were carried out in this plunger-plus-extruder injection molding machine, the first reciprocating screw injection microcellular molding machine was built by Trexel and Engel together in 1998 [10]. This machine marks the milestone of the commercialization of microcellular injection molding and is now the most popular microcellular injection molding machine in the world. Trexel also modified a Uniloy Milacron machine to the first microcellular blow-molding machine in 2000.

One important term, supercritical fluid, is abbreviated as SCF. SCF is the name of the state condition of a gas when the gas is above both its critical pressure and critical temperature; this is discussed in more detail in Chapter 2. It is critical to use SCF to describe a gas if the gas is at a supercritical state. Otherwise, use the general term, gas, if the gas is at any condition from normal atmospheric to supercritical state. Unless otherwise specified, the term of SCF and gas will be used with the conditions above in the entire book.

The injection molding aspect of microcellular foam processing has developed the fastest. The main developed technologies of microcellular injection molding are listed in Table 1.1. The most popular trade name for this technology is MuCell® and is licensed by Trexel Inc. since 2000 (MuCell® is a Registered Trademark of Trexel Inc., Woburn, Massachusetts). Several other injection molding companies and research groups in the world were

TABLE 1.1 Main Developed Microcellular Injection Molding Technologies

Type of Technology	Trade Name	Comment
Microcellular plasticizing unit with special reciprocating screw and barrel to carry out the SCF dosing and injection.	MuCell®	Most popular technology was developed by Trexel, Inc., and has been widely applied worldwide.
Microcellular equipment with special nozzle sleeve for SCF dosing; regular reciprocating screw for injection.	Optifoam®	It was developed by IKV and has been commercialized by Sulzer Chemtech. There are some applications worldwide.
Microcellular dynamic mixer for SCF dosing plus plunger for injection, later modified with reciprocating screw for injection.	Ergocell®	It was developed by Sumitomo-Demag; it has not been common usage on the market yet.
Microcellular equipment with special gas dosing unit in hopper of the regular reciprocating screw for injection.	ProFoam®	It has been invented and tested fully by IKV, and it is still is in the development stage.
Microcellular extruder for SCF dosing plus plunger for injection.	None	It was developed by Trexel and Engel in 1997, and it is not available on market yet.

developing this technology prior to Trexel's announcement of MuCell®. However, they did not finish the commercialization of their technologies for real applications. The MuCell® technology uses a reciprocating screw as the SCF dosing element, and the SCF is injected into the reciprocating screw through the barrel. It makes full use of the shearing and mixing functions of the screw to quickly finish the SCF dosing and to maintain the minimum dosing pressure in the barrel and screw for the possible continuing process of microcellular injection molding. In addition, two other trade names of this technology were found later on: (a) Optifoam® licensed by Sulzer Chemtech [11] and (b) Ergocell® licensed by Demag (now Sumitomo-Demag in 2008) [12]. Optifoam® is a microcellular technology that uses a nozzle as the SCF dosing element. It is a revolutionary change to the traditional SCF dosing method, which adds gas into the barrel. This unique, innovative idea has a special nozzle sleeve made of sintered metal with many ports to let gas go through as tiny droplets. On the other hand, the melt flow through the nozzle is divided into a thin film between the nozzle channel and the sintered metal sleeve. As a result, the gas can diffuse into the melt in a short amount of time. The gas-rich melt is then further mixed in a static blender channel that is located in the downstream of the nozzle dosing sleeve. The advantage of this technology is that the regular injection screw and barrel do not need to be changed. The regular injection molding machine in existence can be easily

changed to use the Optifoam® process. However, only some of these applications have been successful [11]. At K2001, Demag Ergotech introduced its Ergocell® cellular foam system [12]. Ergocell® technology has reached an agreement with Trexel to have their customers pay a reduced price to the MuCell® license when using Ergocell® technology legally. The Ergocell® system is essentially an assembly of an accumulator, a mixer, a gas supply, and a special injection system that is mechanically integrated between the end of the barrel and the mold to put gas into the polymer and create the foam upon injection into the mold. A special assembly needs to be created for each screw diameter. Additional hydraulic pumps and motor capacity must be added to operate the mixer and accumulator injection system. The system only uses carbon dioxide as the blowing agent.

The latest developing foam technology from IKV is the ProFoam® process [13]. It is a new and cheap means of physically foaming injection molding technology. The gas, either carbon dioxide or nitrogen, as the blowing agent is directly added into the hopper and diffuses into the polymer during the normal plasticizing process. The plasticizing unit of the molding machine is sealed off in the feeding section of screw for gas adding at pressure, but feeding of pellets of material occurs at normal conditions without pressure. With this ProFoam® process the part can reduce up to 30% weight via the foaming.

Trexel continues to develop and support the microcellular injection molding process worldwide. There are already over 300 MuCell® injection microcellular molding machines in the world. Through the efforts of many more organizations, more and more advances are being made for the microcellular injection molding process. These organizations include not only original equipment manufacturers (OEMs) licensed from Trexel but also numerous unlicensed organizations, such as universities, and university/industry consortia. All of them are contributing to further advances in microcellular technology.

1.2 ADVANTAGES AND APPLICATIONS OF MICROCELLULAR PLASTICS

The microscopic cell size and large number of cells in microcellular material can reduce material consumption as well as improve the molding thermodynamics, which results in a quicker cycle time. Additionally, the process is a low-pressure molding process and produces stress-free and less warped injection molding products. The major differences between conventional foam and microcellular foam are cell density and cell size. The typical conventional polystyrene foam will have an average cell size of about 250 microns, and a typical cell density in the range of 10^4–10^5 cells/cm^3. Microcellular plastic is ideally defined with a uniform cell size of about 10 μm and with a cell density as high as 10^9 cells/cm^3 [1]. It is possible to make this kind of microstructure

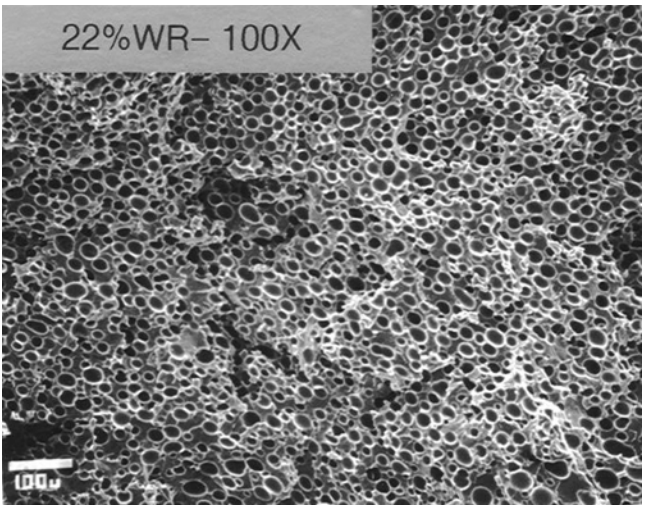

Figure 1.1 Morphology of polystyrene microcellular foam (white bar indicates 100 μm). Average cell size: 25 μm. Cell density: 8.1×10^7 cells/cm^3.

cell density with microcellular injection molding if material and processing are controlled very well. The scanning electron microscope (SEM) morphology of glass-fiber-filled PBT is an excellent example of microcellular injection molding that almost matches the ideal definition of microcellular plastics made by batch process. It is made by using 30% glass fiber and reinforced polybutylene terephthalate (PBT) with a 15% weight reduction (see Chapter 3, Figure 3.12). The cell density is about 8×10^8 cells/cm^3, with an average of 15 μm of uniform cell distribution. However, this microstructure is not always the result of microcellular injection molding. The SEM picture in Figure 1.1 is a more typical microcellular unfilled polystyrene foam made by injection molding that has an average of 25 microns, and has a cell density of about 8.1×10^7 cells/cm^3. The microstructures of industrial parts from microcellular injection molding are characterized by an average cell size on the order of 100 μm, although the real cell size can be varied from 3 μm to 100 μm. However, the cell structure of the microcellular part with microcellular injection molding might not necessarily be defined as the cell density of 10^9 cells/cm^3. The microstructure of ABS has a cell density of about 10^6 cells/cm^3, and it definitely shows a microcellular structure with an average cell size of about 45 μm. The comparisons of average cell sizes between microcellular foam and conventional foam are summarized in Table 1.2. The data in Table 1.2 show that the minimum cell size of conventional foam is about the same size as the maximum cell size of microcellular foam; the maximum cell size of conventional foam is about twice as large as the maximum cell size of microcellular foam. Usually the cell density of the conventional foam is about 10^2 to 10^6 cells/cm^3. However, the cell density of the microcellular foam is 10^6 cells/cm^3 or higher.

TABLE 1.2 Comparisons Among Conventional Foam, Microcellular Foam, and Regular Solid

Item of Comparison	Conventional Foam	Microcellular Foam	Regular Solid
Average cell density (cells/cm^3)	10^2–10^6	10^6–10^9 or higher	NA[a]
Average cell size (μm)	250 or larger	3–100	NA
Sink mark	No	No	Yes
Cell structure	Open or closed	Closed, or a few partially open	NA
Cell size (or density) distribution across the part of thickness	Nonuniform, the distribution pattern across the thickness: small (side near skin)–big (center)–small (side near skin)	Uniform	NA
Maximum flow path length-to-thickness ratio	50–100:1	Up to 350:1	Up to 300:1
Hold	Short time	No	Yes
Wall thickness	Thick wall, 4–9 mm and up to 50 mm	Thin wall, 0.5–3 mm, possibly up to 6 mm with short flow ratio and fast injection speed	0.5–6 mm, up to 9 mm
Residual stress after molding	Nil for ≤4 mm thickness, 0.5–3 MPa in the thick part of 10–20 mm	Nil	Yes
Surface finish	Poor	Between conventional foam and solid	Class A
Cycle time reduction	Long cycle time because of thick part, 1–8 minutes, depending on the wall thickness	Up to 50% reduction versus solid part for ≤4 mm. Thickness. Over 4 mm is similar to traditional foam on the left.	NA

TABLE 1.2 ***Continued***

Item of Comparison	Conventional Foam	Microcellular Foam	Regular Solid
Weight reduction	Some weight reduction is possible. NA if the stiffness is needed to match the solid thin part.	0–15% weight reduction	NA
Maximum injection pressure reduction	20–50%	20–60%	NA
Clamp tonnage reduction	Up to 50%	Up to 60%	NA
Energy saving	About 15%	Up to 30%	NA
Dimension stability, such as warpage, shrinkage, etc.	Good	Excellent	Poor
Toughness	Increase compared to the same solid material	Increase significantly compared to the same solid material	The same initial solid material served as baseline here
Stiffness	Stiff with extra thickness	Flexible	Between microcellular and conventional foam
Other mechanical properties	Decrease with the weight reduction %	Decrease with the weight reduction %	100% for comparison with foam properties
Mold wearing	Less	Less	Normal
Mold cost	Cheap	Cheap	Expensive
Material	PE, PP, PC, POM, ABS, PS, etc.	Any material	Any material
Color	Natural white color may save white color cost	Natural white color may save white color cost, or light color	No savings for white color cost
Postprocess	Needed	May need	None
Weld line strength	Poor	Good	Excellent

TABLE 1.2 ***Continued***

Item of Comparison	Conventional Foam	Microcellular Foam	Regular Solid
Insulation of heat, sound	Good	Excellent	Normal
Application	Insulator, structure part with stiffness, impact absorber, wood replacement, non-sink-mark appearance part, dimensional stable part.	Same as both conventional foam and regular solid parts. In addition, for precise molding parts with sink mark and no warpage; fiber disorientation requirement, tonnage saving, cycle time saving, and material saving, difficult mold filling parts, and soft touch surface with strength.	Widely used except for insulator

[a]NA, not available.

The cell size in the foam mainly determines the property differences between conventional foam and microcellular foam. Table 1.1 shows the comparisons among injection molding parts made by conventional foam, microcellular foam, and regular solid. It is clear that microcellular foam has more advantages than conventional foam. Microcellular foam overcomes the major disadvantages of conventional foam, such as a long cycle time and a thick wall. The most important advantages of microcellular foam can be summarized as follows:

- The main advantage of structural foam molding (one of the conventional foams) is to increase stiffness without increasing the weight of the component. Microcellular foam can be made for this target as well, by redesigning thin wall structures and by creating a nice cell structure to save material (weight reduction by a thin wall) and cost (shorter cycle time).
- The microcellular process can be used for thin-wall solid parts that are difficult to make full mold filling from flow restrictions, which results in either clamp tonnage shortage or injection pressure limit.
- Microcellular technology allows mold filling without foaming because the gas-rich melt reduces viscosity significantly.

- The microcellular process almost eliminates all dimension stability problems, such as sink mark, flatness defects, warp, and residual stress after molding due to the elimination of pack and hold phases during molding.
- The microcellular process dramatically reduces cycle time if the part is designed properly.
- Microcellular processing equipment can be designed to save more energy since the peak of injection pressure is not necessary and also saves up to 50% of clamp tonnage.

The disadvantages of microcellular foam are the same as conventional foam, such as poor surface finish, strictly balanced runner system for multicavity mold, nontransparent application only, and complicated processing technology.

1.3 PATENTS AND PUBLICATIONS COVERING MICROCELLULAR INJECTION MOLDING TECHNOLOGY

There have been many patents issued for microcellular injection molding since 1998. The major patents, directly or indirectly related to microcellular injection molding technology, are listed here:

Pierick, D. E., et al., International Patent Application WO 98 31 521 A2 (1998)

Park, C. B., et al., U.S. Patent No. 5,866,053 (1999)

Pierick, D. E., et al., International Patent Application WO 00 26 005 A1 (2000)

Xu, J., International Patent Application WO 00 59 702 A1 (2000)

Michaeli, W., et al., German Patent DE 19 853 021 A1, (2000)

Anderson, J. R., et al., International Patent Application WO 01 89 794 A1 (2001)

Xu, J., U.S. Patent No. 6,322,347 (2001)

Burnham, T. B., et al., U.S. Patent No. 6,284,810 (2001)

Anderson, J. R., et al., U.S. Patent No. 6,376,059 (2002)

Gruber, H., et al., U.S. Patent Application No. 0,056,935 A1 (2002)

Pierick, D. E., et al., International Patent Application WO 02 090 085 A1 (2002)

Kim, R. Y., et al., International Patent Application WO 02 081 556 A1 (2002)

Vadala, J. P., et al., International Patent Application WO 02 026 484 A1 (2002)

Kishbaugh, L. A., et al., International Patent Application WO 02 026 485 A1 (2002)

Kishbaugh, L. A., et al., International Patent Application WO 02 072 927 A1 (2002)
Xu, J., U.S. Patent No. 6,579,910 B2 (2003)
Anderson, J. R., et al., U.S. Patent No. 6,593,384 (2003)
Dwivedi, R. K., U.S. Patent No. 6,759,004 (2004)
Cardona, J. C., et al, U.S. Patent No. 6,926,507 (2005)
Anderson, G., et al., U.S. Patent No. 7,172,333 (2007)
Xu, J., U.S. Patent No. 7,267,534 (2007)
Xu, J., et al., U.S. Patent No. 7,318,713 (2008)
Kishbaugh, L.A., et al., U.S. Patent No. 7,364,788 B2 (2008)
Xu, J., et al., U.S. Patent No. 7,615,170 B2 (2009)

There are many publications regarding the technology behind microcellular injection molding. They cover both the fundamentals and real practices in industry. However, it is well known a huge gap exists in fundamentals and realities. Hopefully, this comprehensive coverage in the book will help bridge this gap and will enable readers to apply the concepts in a straightforward manner.

1.4 OUTLINES OF THE BOOK

This book presents the microcellular history and a specific short history of microcellular injection molding in Chapter 1. Then, in Chapters 2 and 3, the fundamental knowledge of microcellular injection molding is covered. With the understanding of the principles of microcellular processing, a review of materials and details of design for microcellular injection molding are well discussed in Chapters 4 and 5. Moreover, injection molding makes the foaming process more complex. Therefore, both theory and experiments are needed for good analyses of microcellular process. Chapter 6 uses the fundamental guidelines in previous chapters to analyze the specific processing procedures one by one with a combination of theory and empirical data. Some comparisons among different gas-entrained processes, such as gas assistant, microcellular extrusion, microcellular blow molding, and structural foam molding are discussed in Chapter 6. It is also important to know the differences between regular injection molding and microcellular injection molding, which is discussed briefly in Chapter 6. To realize the processing requirements in Chapter 6, the equipment designing rules are introduced in Chapter 7. It will generate further insight on both the future development and the efficient operation. After understanding normal microcellular injection molding, more specialized microcellular injection molding processes are discussed in Chapter 8. All commercialized special processes and most developing special processes are covered in this chapter. In addition, the modeling of microcellular injection

molding is also presented in Chapter 9. Some PVT data and rheology data of the gas-laden polymer melt are given in Chapter 9. The necessary postprocesses and basic test procedures are briefly introduced in Chapter 10. Finally, application in the market is covered in Chapter 11, and cost analyses are presented in Chapter 12.

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