

## Advances in Microcellular Injection Moulding

G. Llewelyn<sup>a</sup>, A. Rees<sup>a</sup>, C.A. Griffiths<sup>a</sup>, S.G. Scholz<sup>b</sup>

<sup>a</sup> *College of Engineering, Swansea University, Swansea, SA1 8EN, UK*

<sup>b</sup> *Institute for Applied Computer Science, Karlsruhe Institute of Technology, 76344  
Eggenstein-Leopoldshafen*

### Abstract

Injection moulding (IM) is a well-established replication process for the cost-effective manufacture of polymer-based components. The process has different applications in fields such as medical, automotive and aerospace. To expand the use of polymers to meet growing consumer demands for increased functionality, advanced IM processes have been developed that modifies the polymer to create microcellular structures. Through the creation of microcellular materials, additional functionality can be gained through polymer component weight and processing energy reduction. Microcellular injection moulding (MIM) shows high potential in creating innovation green manufacturing platforms. This review article aims to present the significant developments that have been achieved in different aspects of MIM. Aspects covered include core-back, gas counter pressure (GCP), variable thermal tool moulding and other advanced technologies. The resulting characteristics of creating MIM components through both plasticising agents and nucleating agents are presented. In addition, the article highlights potential areas for research exploitation. In particular, acoustic and thermal applications, nano-cellular IM parts and developments of more accurate simulations.

### Key Words

Polymer processing

Injection Moulding (IM)

Microcellular polymers

Microcellular Injection Moulding (MIM)

Green manufacturing

MuCell®

## 1. Introduction

In the early 1980s, the Massachusetts Institute of Technology (MIT) invented microcellular processing in the Industry Polymer Processing Program<sup>1</sup>. The aim of this project was to reduce material usage, reduce final part weight and modify the resulting material properties through the introduction of small spherical cells into the polymer-based products<sup>2</sup>. The initial publications and thesis' from this research institute discovered the proof of concept and advanced the fundamental theories behind the technology<sup>3-12</sup>. This pioneering proof of concept work focused on batch processing and extrusion with the first U.S. patent being issued in 1984<sup>13</sup>. The first commercial activity followed in 1998 when Axiomatics Corp., known today as Trexel Inc., built the first reciprocating screw microcellular injection moulding (MIM) machine<sup>14-16</sup>.

MuCell®, Trexel's patented MIM technology, was established in 2000<sup>14</sup> and they partnered with major injection moulding (IM) companies<sup>17</sup>. Other MIM technologies are available; Optifoam®, Ergocell® and ProFoam® which all use variations of MuCell®<sup>18-20</sup>.

Prior to the development of microcellular technology, conventional foam was used to produce polymer parts with cellular structure<sup>21</sup>. Moreover, this technology is limited to cell densities is much lower than that obtainable from MIM and with poor mechanical properties<sup>14</sup>. However, MIM creates parts that has reduced polymer content, lower final part weight and processing energy requirements<sup>15</sup>. This technique uses blowing agents which are added to the raw polymer and fed through the hopper in a regular IM cycle. Blowing agents can be split into either physical blowing agents (PBA) or chemical blowing agents (CBA). PBAs are where the agent is forced into the polymer melt whereas CBA release inert gas upon heating into the polymer<sup>22</sup>. CBAs used are ammonium, sodium bicarbonate or complex inert gas-releasing materials<sup>21,23</sup> and typically produce final parts with lower cell densities and larger average cell size<sup>24</sup>.

This article provides a review of the research activities conducted in the field of MIM. The principle of the technology is presented together with applications. The article identifies the major MIM academic research area with particular reference to research into all techniques to improve the surface defects associated with MIM. The final section of the article discusses the knowledge base and suggests future direction for MIM research activity.

## 2. MIM

The following section provides the basic knowledge of the MIM process by comparing the process to conventional IM and alternative foaming methods for the production of polymer-based components.

### 2.1 Conventional IM

The IM process provides a cost effective manufacturing platform for producing thermoplastics products <sup>25</sup>. This process can be divided into three key stages: plastication (polymer granules converted to molten phase <sup>25</sup>), mould filling (molten polymer forced into a mould, including compensation for shrinkage <sup>26</sup>) and cooling (where this molten polymer cools inside the mould <sup>27</sup>) <sup>28</sup>. These fundamental process steps are also witnessed within the process of MIM; however, the fundamental process steps are modified to accommodate the change in the characteristics of the material being processed. Figure 1 shows the difference in machine configuration when comparing conventional IM and MIM. However, Lee et al. proposed additional machine configurations whereby high void fractions and higher cell density can be achieved <sup>29</sup>.

#### insert Figure 1

**Figure 1** Process schematic to illustrate the additional modifications required of a conventional IM machine to facilitate MIM processing (adapted with permission from Springer Nature) <sup>30</sup>

### 2.2 MIM process

The benefits of MIM processing are witnessed in the weight reduction of the resulting parts which ranges from 0 to as much as 15% for some applications <sup>14</sup>. This is beneficial as the price of raw materials for the polymer has increased dramatically in recent years <sup>31</sup>.

When compared to conventional IM, for MIM, the maximum injection pressure and clamp tonnage can be reduced by as much as 60% for microcellular foaming which translates into a 30% energy saving <sup>14</sup>. Other major advantages of MIM are that no residual stress is created, 50% reduction in cycle time for thin walled parts, increased toughness, improvement in heat and sound insulation characteristics <sup>14</sup>. Also, the mechanical properties of the underpinning process tooling can be reduced to reflect the reduction in both injection pressure and clamp tonnage <sup>14</sup>. In low-pressure foaming, no packing and holding is required in the MIM process; this is performed by cell nucleation and expansion <sup>32</sup>. However, recent advancements in the technology have shown that by incorporating packing time in MIM (high-pressure

foaming), the final cell morphology can be improved as the residual, larger cells that nucleate during the filling stage, are dissolved into the melt and then nucleate in a more controlled manner during cooling<sup>33-35</sup>.

## 2.3 MIM process stages

In MIM, there are 4 key stages. These are: (1) Super Critical Fluid (SCF) mixing and dissolution in the polymer melt, (2) cell nucleation, (3) growth of the cells and (4) shaping within the mould<sup>15</sup>. Figure 2 provides a schematic of the stages.

### insert Figure 2

Figure 2 Microcellular foaming process<sup>1</sup>

#### 2.3.1 SCF mixing and dissolution

When processing with MIM, SCF is injected into the barrel in order to generate gas-polymer solution<sup>36</sup>. The SCF enters the barrel with a pressure and temperature above the critical point of the gas (Figure 3). During this initial point of entry into the barrel, the SCF forms large gas droplets in the polymer due to the flow of gas being interrupted by the rotation of the injection screw with the barrel. Mixing the SCF under pressure has proven to enhance the solubility within the polymer to a larger degree than obtained through an increase in temperature<sup>37</sup>. There are 5 major factors which determine the size of the gas droplets. These are: gas and molten polymer pressure, flow rate of the gas, molten polymer viscosity, screw rotation speed and the gas injector orifice diameter<sup>14</sup>.

The Weber number ( $W_e$ ) also plays a crucial role into the formation of the gas droplets and how they are broken down in the polymer melt, inside the barrel.  $W_e$  is characterised as the ratio of shear force to the surface tension force<sup>2</sup>. Cell nucleation is the next major step and by the time this phase commences, the gas-polymer solution should be in a single-phase state which is a homogenous solution of gas and polymer containing the gas droplets. The single-phase state must be maintained throughout the entirety of the barrel until the melt enters the mould. To achieve the single-phase state, a shut off nozzle (cold runner system) or valve gate (hot runner system) must be used<sup>14, 38, 39</sup>. This single-phase solution is critical in obtaining strong, consistent parts and is the most challenging element of the technology<sup>40</sup>.

#### 2.3.2 Cell nucleation

Cell nucleation can be either homogenous or heterogeneous. Both need to be induced by a rapid thermodynamic instability<sup>41</sup>: a rapid pressure drop or temperature variation. In injection moulding, the best solution to this is the application of a pressure drop; created with a change in area using the conservation equation<sup>42</sup>. In the case of the injection moulding process, the easiest place to cause a large pressure drop is in the nozzle orifice or the valve gate as the narrow orifice causes up to >1GPa/s pressure drops<sup>14</sup>.

### 2.3.3 Cell growth

After the nucleation process, the cells grow as the gas-polymer solution remains at an elevated temperature. The shot size in MIM is less than would be used in conventional IM. The reduction in shot size provides the necessary space for the cells to grow. Providing sufficient gas to the nuclei within the melt enhances the stability of the cell as they continue to grow<sup>14</sup>.

### 2.3.4 Shaping within the mould

The final stage of the MIM process is the shaping within the mould. Not only does the polymer material shape itself to the mould, but it also builds up the skin-cell structure. During cooling, the cells retain their size and shape through residual gas pressure contained within the cells and essentially push the melt against the corresponding mould walls<sup>14</sup>.

MIM parts exhibit a lower shrinkage and warpage to that of conventional IM. Holding pressure and time have the most significant effect on shrinkage and warpage in conventional IM. Whilst in MIM, SCF content and injection speed have found to be the most crucial input factors<sup>43</sup>.

## 2.4 Super Critical Fluids

SCFs are utilised in MIM as opposed to a gas or a fluid. SCF's are preferred as both gas or fluid offer poor solubility below their critical point. Figure 3 represents a Pressure-Temperature graph for a typical substance, in which the various phases and SCF region are highlighted<sup>44</sup>.

### insert Figure 3

**Figure 3** Pressure-Temperature graph phases for gas<sup>42</sup>

The highlighted SCF region is greater than the critical pressure ( $P_{cr}$ ) and critical temperature ( $T_{cr}$ ). Above both the  $P_{cr}$  and  $T_{cr}$ , the gas diffuses into the molten polymer at an

increased rate. In this state, the gas is neither a gas or a liquid and it acts like both simultaneously. Some examples of the typical values required to reach this state for Nitrogen (N<sub>2</sub>) and Carbon Dioxide (CO<sub>2</sub>) are: -147.0 °C and 31.1 °C for T<sub>cr</sub> and 3.4 MPa and 7.22 MPa for P<sub>cr</sub> respectively <sup>2,6</sup>.

Previous research has explored the application of creating SCF by using; Argon, Helium, Water and Propane. However, they have limitations with regards to; price, grade variation, machine degradation and flammability issues <sup>14, 45</sup>. Therefore, for the application of MIM, N<sub>2</sub> and CO<sub>2</sub> are generally utilised as both are inert gases and relatively cheap. However, their interaction with polymers vary; which influences the integrity of the final part within the MIM process <sup>14, 46</sup>. N<sub>2</sub> has proven to achieve lower solubility within the molten polymer when compared to CO<sub>2</sub> <sup>46</sup>.

#### 2.4.1 Alternatives to SCF

Research has been conducted on modifications to the standard SCF process developed by MuCell®. In particular, Yusa et al. have successfully shown that machine energy costs and material usage can be reduced by using N<sub>2</sub> and CO<sub>2</sub> at lower pressures than the Super Critical (SC) state <sup>47</sup>. This was achieved by designing and implementing a similar system to the MuCell® setup. However, in this research the gases were injected directly from a pressured bottle at 12MPa and 6MPa for N<sub>2</sub> and CO<sub>2</sub> respectively. An additional venting system was also added to allow for excess gas evacuation when the maximum solubility level was reached <sup>47</sup>. The results concluded that microcellular PP foams could be produced with an average cell

Wang et al., have developed a MIM system which uses 5 MPa air pressure as the PBA. PP was used in the investigation and results were compared to against test parts processed using N<sub>2</sub> and CO<sub>2</sub> as the SCFs <sup>48</sup>. Cell diameters of 7 um and cell density of 1.63x10<sup>9</sup> cells/cm<sup>3</sup> were achieved <sup>48, 49</sup>.

Peng at al. have also investigated a variation to the standard SCF for MIM by using distilled water with low levels of salt as the PBA <sup>50</sup>. . Peng et al., integrated a water metering system into the hopper to administer high temperature water along with the polymer. The resultant solution formed a pressurised vapour and recrystallized salt crystals which are uniformly dispersed within the PC melt matrix. This system did not replicate the poor surface finishes that is typically witnessed in MIM. Another major benefit to system developed by Peng et al., is that conventional IM machines can be utilised by adding the metering system for the water/salt solution to the hopper <sup>50</sup>.

Cabrera et al., developed a system whereby pressurised water pellets containing carrier particles of activated carbon (CB) are fed through the hopper opposed to injecting SCF directly into the barrel<sup>51</sup>. Similar to MIM, this method reduced the packing pressure, sink marks and warpage. The research concluded the technology could create foamed structures. However, the resulting cell size was in the region of 100-500  $\mu\text{m}$ <sup>51</sup>.

## 2.5 Cell structure

Microcellular foaming processes produce significantly smaller cell structures than regular foaming produced by CBAs<sup>52</sup>. In particular, the smallest cell structure achieved through CBA is 250 $\mu\text{m}$ . Typically, microcellular foaming produces cells in the range of 3-100 $\mu\text{m}$ <sup>14</sup>. Figure 4 illustrates a typical part structure processed with MuCell® IM.

### insert Figure 4

**Figure 4** MuCell® processed PP-Talc part with N<sub>2</sub> as the blowing agent

Shaayegan et al. investigated the visualisation of the MuCell® process by using a unique mould which allows users to see within the cavity. Within the study Polystyrene (PS) in combination with CO<sub>2</sub> were used<sup>53-56</sup>. The processing variables of injection speed, flow resistance of the gate, content of the blowing agent, melt flow rate and addition of talc were investigated. It was concluded that the injection speed and the resistance of the gate did not affect the resulting cell density whilst the dissolved gas content within the polymer melt affect cell density. Furthermore, by decreasing the melt flow rate, more cells were created by inducing greater local stresses. Also satellite cells were observed whereby additional cells form around an existing cell site, resulting in a cell which has two circumferences and thus, forming a nonhomogeneous cell structure<sup>54</sup>.

## 3. Limitations of microcellular technology

### 3.1 Surface defects

To achieve a moulding free of surface defects when processing with both CBA and PBA requires the use of variothermal technique<sup>57,58</sup>. Other potential drawbacks when microcellular processing is a reduction in weld line strength when compared against conventional IM. Another limiting constraint is that MIM cannot produce transparent parts due to inherent visual defects within the process<sup>14</sup>.

The surface finish defects witnessed in MIM are a result of the fountain flow affect (Figure 5) which is within the cavity of the mould <sup>59, 60</sup>. As the polymer melt solution flows through the mould, the polymer melt front solidifies outwards towards the mould surface while the inner area of the melt continues to flow <sup>61</sup>. The polymer melt solidifies on the mould surface and the cells at the advancing melt front are stretched towards the mould surface causing swirl marks <sup>16</sup>.

### **insert Figure 5**

**Figure 5** Fountain flow with (a) advancement of the skin layer and (b) the increase and formation of the skin layer <sup>62</sup>

Lee et al. demonstrated that by controlling the cell nucleation rate within the polymer melt solution through the modification of both SCF concentration and material formulation, surface defect free parts could be produced <sup>63</sup>. This was achieved by using low density polyethylene (LDPE) and polypropylene (PP) with a N<sub>2</sub> content of 0.173% or less <sup>63</sup>. The research demonstrates that when smaller concentrations of N<sub>2</sub> are used, there is a reduction in supersaturation which results in surface defect free parts with a weight saving of up to 8% <sup>63</sup>.

### **3.2 Weld line strength**

Turng et al. have investigated the effect of process parameters on weld line formation within products produced through MIM <sup>32</sup>. In the research, the processing parameters of melt temperature, shot size, SCF level and injection speed were analysed. The study found that for MIM, shot size had the highest influence on the weld line strength. In particular, weld line strength is increased with an increase in shot size, melt temperature and injection speed but the SCF level had little effect. In addition, a 19.48% polymer weight reduction was achieved during this study. However, reductions in mechanical characteristics are witnessed as voids are formed on the weld line due to coalescence of cells <sup>32</sup>.

### **3.2 Alteration of the mechanical properties**

The resulting mechanical strength of components produced through MIM plays a significant role to expand their applications <sup>64, 65</sup>. Gomez-Monterde et al., investigated using MuCell® in combination with a Acrylonitrile Butadiene Styrene (ABS) component <sup>66</sup>. In the research, square components were produced having characteristics of solid, 10% weight reduction and 17% weight reduction. The research concluded that flexural modulus and tensile



strength decreased with an increase in weight reduction. The empirical data was also simulated to accurately present the modification in material characteristics. Also, the fracture behaviour of the parts were examined using the crack tip opening displacement (CTOD) parameter along with the fracture toughness ( $K_{Ic}$ ). It was observed that  $K_{Ic}$  declines with increasing weight reduction while the CTOD improves <sup>66</sup>.

## **4. Advanced microcellular processing technology**

### **4.1 Co-injection moulding**

During the MIM process, a skin layer of nonporous material is usually formed with a microcellular featured core <sup>67</sup>. Co-injection moulding in conventional IM produces similar structured parts to this however instead of a porous inner structure an addition polymer can be introduced <sup>68</sup>.

Turng and Kharbas have shown that co-injection moulding technology can be used in combination with MIM <sup>69</sup>. Cells of 8-12  $\mu\text{m}$  were produced within the outer layer of pure polymer. In addition to the benefits of MIM this process produced components whereby the swirl marks were eliminated <sup>69</sup>.

### **4.2 Core-back processing**

When process MIM components the pressure differential between the injection barrel and subsequent tooling facilitates the nucleation within the polymer. Ruiz et al. have developed the concept to increase nucleation by inducing a further pressure drop through core-back processing <sup>70</sup>. The core-back process is achieved through the retraction of the moving part of the mould after it has been filled with the polymer melt <sup>71</sup>. This technique achieves high expansion foam due to the mould cavity suddenly increasing and thus, decreasing the melt pressure <sup>72</sup>. Void fractions as high as 80% have been achieved in MIM with core-back processing for the manufacture of ultra-light weight components <sup>73, 74</sup>.

Shaayegan et al. investigated the effect of melt compressibility and pressure drop rate on the resulting cell nucleation behaviour when using core-back in combination with MuCell® with high-pressure foaming (with packing pressure). Figure 6 shows the injection stage whereby the pressure of the polymer returns back to a level above the solubility pressure by applying packing pressure. The research concluded that when using a PS polymer and  $\text{CO}_2$ , higher cell density is achieved with a packing pressure greater than 20MPa. Also, a percentage of cells that had nucleated during the mould filling process, could sustain the pressure in the cavity until the core-back operation began. This resulted in an increase in the polymer solutions

mixture compressibility and a subsequent a lower obtainable pressure-drop rate from the core-back operation. Also, by increasing the packing pressure, cells can be removed during this stage. Thus resulting in a faster pressure-drop rate, higher cell density and more homogenous cell structure <sup>33</sup>.

insert Figure 6

**Figure 6** High-pressure MIM with core-back: (a) cell formation during mould filling; (b) packing pressure applied to re-dissolve nucleated cells back into the polymer melt: (i) full shot; (ii) polymer melt packing; (iii) total dissolution of nucleated cells; (c) nucleation of new cells during mould opening. (republished with permission of Elsevier.) <sup>33</sup>

Ishikawa et al. have investigated core-back processing in combination with MuCell® processing. The research analysed the process through a visual observation in a specially built mould. The experimental results were also validated through numerical analysis and concluded that an increase in the cell density and decrease in cell growth rate were observed when applying a core-back processing <sup>75</sup>.

With regards to the use of core-back processing, all research correlate that better nucleation is witnessed within the structure of the final part <sup>33, 70, 71, 75</sup>. This improvement in nucleation is attributed to the further rapid pressure drop achieved by exposing the inside of the mould to additional atmospheric pressure <sup>75</sup>.

### 4.3 Gas Counter Pressure

Gas Counter Pressure (GCP) can also be used for MIM. Typically, pressurised gas is present in the mould prior to the polymer melt being injected. The GCP is maintained until the commencement of the injection stage. This delay in nucleation has proved to reduce the swirl marks commonly witnessed in components produced via MIM <sup>76</sup>.

In a study by Bledzki et al., it was shown that swirl marks can be removed with the use of GCP. In particular, surface roughness ( $R_z$ ) was reduced from 23.11 $\mu\text{m}$  to 0.85 $\mu\text{m}$  <sup>77</sup>. The investigation also concluded that an improvement in tensile and impact strength was witnessed <sup>77</sup>. In further research by Bledzki et al., two studies were produced to investigate the effects of GCP processing. In the first study, PC microcellular parts with an average cell size of 10  $\mu\text{m}$  or less were successfully produced. In the second study, a sandwich structure was developed which contained a thick skin layer and a distinctive boundary between the skin layer and the

foam core <sup>78</sup>. Both studies also showed an improvement in the resulting toughness when compared to conventional IM <sup>78</sup>.

Chen et al., investigated the effects of GCP and mould temperature on the resulting surface quality and cellular morphology when using the MuCell® process <sup>79</sup>. The research concluded that when GCP was introduced in isolation; good surface finish was witnessed. However, the skin thickness increased which results in a higher density of the final part. When mould temperature was increased the skin thickness was reduced but the cell homogeneity is poor <sup>79</sup>. Also, the investigation demonstrated that by combining both GCP and elevated mould temperatures; an increase in both the surface quality and cellular morphology can be achieved <sup>79</sup>.

The results obtained by Chen et al., also proved that GCP is effective at reducing surface defects. In particular, when processing a PS polymer a surface roughness improvement of more than 90% was achieved <sup>80</sup>. Furthermore, it was found that when applying a holding time of 10 seconds, the parts exhibited no foaming until the melt is solidified <sup>80</sup>.

Lee et al., have proposed a combination of both GCP and core-back processing with high density PE (HDPE). to produce Class A surface finishes <sup>81</sup>. When processing with GCP in isolation the pressure drop after the pressure release was not constant and therefore caused poor cell structure and poor surface finish. However, when core-back was applied in combination with GCP the pressure drop was constant throughout the whole part and a uniform cell structure with excellent surface finish was achieved <sup>81</sup>.

#### **4.4 Vario-thermal moulding**

In IM elevated tooling temperatures can be used to enhance the surface quality of moulded components This works by heating the mould before injection and then rapidly cooling it once the mould is filled. This process is called vario-thermal moulding <sup>82, 83</sup>. Xiao et al., proved that through the introduction of vario-thermal using electric heating and water cooling in MIM (schematic of the mould setup in Figure 7); the resulting surface defects commonly attributed to MIM can be eliminated <sup>84</sup>. In this research, Polyformaldehyde (POM) was MIM with additional mould surface temperature (contact temperature) above 150 °C, the final surface appearance replicated the characteristics of a solid part. This is mainly due to the re-dissolution of trapped surface gas between the polymer melt and the mould cavity during initial filling <sup>84</sup>.

Chen et al., investigated the resulting improvement in surface quality through the vario-thermal moulding technique <sup>85</sup>. Induction heating was used to elevate the mould temperature

from 100 °C to 160 °C<sup>85</sup>. This decreased the surface roughness of PC from 25µm to 6.5µm<sup>85</sup>. It was also concluded that 180 °C was the optimum temperature for the mould when producing PC parts. Mould temperatures above 180 °C did not improve the surface roughness any further<sup>85</sup>. This research showed that through the minimisation or removal of the cells approaching the surface of the mould during filling, visual surface defects can be mitigated due to no cells being present on the melt/mould shearing interface<sup>85</sup>.

#### **insert Figure 7**

**Figure 7** Mould with vario-thermal capability, (a) heating stage (b) cooling stage (republished with permission of Elsevier.)<sup>84</sup>

Hopmann et al., directly compared various mould structure finishes (mirror, leather, grained and dashed) when used in combination with vario-thermal MIM using a PC/ABS polymer blend<sup>86</sup>. The research concluded that when the polymer glass transition or crystallisation temperature is equal or lower than the mould contact temperature, good surface finishes can be achieved regardless of the mould structure finish when processing through MIM<sup>86</sup>.

#### **4.5 Mould temperature insulation coatings**

Lee et al. have reported significant improvements on the surface quality of MIM through the application of thin film tooling insulation coating<sup>87</sup>. Varying thickness layers of polytetrafluoroethylene (PTFE) were added to the inner surface of the mould to increase the interfacial temperature between the mould and polymer melt. A 175µm layer of PTFE was found to be the thinnest mould insulator insert that could be used to keep the interfacial temperature above the  $T_g$  during filling. This processing configuration induced conformal cooling and eliminated the fountain flow effect and mitigating swirl marks<sup>87</sup>.

#### **insert Figure 8**

**Figure 8** Heat dispersion in a mould with (a) no mould insulator and (b) with a mould insulator (republished with permission of John Wiley & Sons.)<sup>87</sup>

Figure 8 illustrates the concept of the molten polymer reaching the insulator and not the mould wall as a result of increased temperature when compared with no insulator<sup>87</sup>. In this case, polytetrafluoroethylene (PTFE) was added to the mould wall before the MIM process. It

was shown that a 175 $\mu\text{m}$  PTFE layer was sufficient to keep the interfacial temperature above the crystallisation temperature of LDPE<sup>87</sup>. Also, the surface roughness of the parts produced in this research were reduced<sup>87</sup>.

Similar research was performed by Chen et al.<sup>88</sup>. In the research, PC was used in MIM with a polyethylene terephthalate (PET) mould insulator<sup>88</sup>. The surface roughness of the final parts was reduced drastically with the integration of the a 0.125 $\mu\text{m}$  PET film. In particular, the surface roughness decrease from 26 $\mu\text{m}$  down to 5.6 $\mu\text{m}$ <sup>88</sup>. With a 0.188 mm film, the surface roughness was further reduced to 1.8 $\mu\text{m}$ , giving a 93% improvement from the standard microcellular injected moulded part<sup>88</sup>. Researchers have found similar results by integrating the mould insulation into one side of the mould. In particular, the insulation layer only being used on surfaces that require visual functionality. The results concluded that the parts manufactured displayed signs of asymmetric cooling. This was caused by the mould insulator reducing the heat transfer coefficient, whilst the conventional mould surface remained constant<sup>89</sup>.

#### **4.6 Material alteration**

The polymers used in IM can be either a pure polymer or polymer blend. Also, fillers can be used to enhance the properties of materials and reduce shrinkage<sup>90</sup>. Xi et al., have shown that glass fibres (GF) can be added to MIM to achieve better mechanical strength<sup>91</sup>. In particular, it was found that the MIM process decreased the fibre breakage by 30% compared to conventional IM which in turn, contributed to an improvement in fibre orientation<sup>92</sup>.

When processing with MIM, the addition of material fillers has the benefit of producing higher cell density and smaller cell size as they aid cell nucleation and enhance melt strength<sup>93</sup>. Xin et al., have researched a novel filler of waste ground rubber tire (WGRT) to PP, forming thermoplastic polyolefin (TPO)<sup>94</sup>. The research concluded that for the application of MIM the addition of WGRT to the PP results in enhanced formation of the cell structure<sup>95</sup>.

Zhang et al., investigated the feasibility of using polymer blends for MIM. In the study, three different PP/Polyethylene (PE) blends were investigated to analyse the resulting crystallinity, melt strength and cellular structure<sup>96</sup>. The research concluded that for all of the PP/PE blends, the melt strength was initially enhanced until a PE content of 30% was achieved<sup>96</sup>.

Cross-linking agents have also shown to increase the molecular weight, storage modulus and viscosity of Thermoplastic Polyurethane (TPU) thereby increasing melt strength when foamed in the MIM process<sup>97</sup>.

#### 4.6.1 Carbon Nanotubes

Li et al., have investigated the resulting MIM cell morphology and mechanical properties of polyetherimide (PEI) with multi walled carbon nanotubes (MWCNT) fillers. It was shown that MWCNT have a significant effect on the cell nucleation <sup>98</sup>.

MWCNT have also been added to PP during the MIM process by Ameli et al., to demonstrate how this process can produce conductive components <sup>99</sup>. The cellular morphology and electrical conductivity were analysed through varying the processing conditions of: injection flow rate, gas content, melt temperature, void fraction and cavity location on the resulting microstructure <sup>99</sup>. The research concluded that a 30% weight reduction and six times greater electrical conductivity can be obtained when compared to conventional IM <sup>99</sup>.

Wang et al., have used PLA/graphite nanocomposites in MIM with core-back processing for EMI shielding applications <sup>100</sup>. The graphite not only promoted the crystallisation and viscoelastic behaviour of the PLA foam, but also produced a final conductive part. The final EMI shielding effect was measured to be 45 dB whilst also increasing the toughness <sup>100</sup>.

#### 4.6.2 Plasticising agents

The absorption of gas into polymers effects the polymer in many ways. Typically, reduction of the glass transition temperature ( $T_g$ ), also known as plasticisation, and the free volume space is increased <sup>101</sup>. Along with pressure and temperature, the solubility of gas in the polymer is also a critical parameter in controlling the phase separation and the foam morphology <sup>102, 103</sup>. In general, volume swelling increases with increased pressure or by decreased temperature of the polymer/gas solution in MIM <sup>104</sup>. The Sanchez-Lacombe equation provides a theoretical approach to the parameters required for the addition of SCF into the polymer solution <sup>105</sup>.

Mahmood et al., have added Dimethyl Ether (DME) to PS in their research to investigate its effects on plasticisation <sup>106</sup>. This research was carried out using laboratory scale microcellular processing. The results conclude that with an increase of DME in PS, the solubility of CO<sub>2</sub> into the polymer solution was increased <sup>106</sup>.

#### 4.6.3 Nucleating additives

Talc has previously been added to polyolefins in IM as it has been shown to improve the mechanical properties, melt viscoelasticity and promote crystallisation without hindering

the processabilities of such polymers as PP <sup>107, 108</sup>. Also, the addition of talc to polyolefins in MIM has been seen to improve the polymer melt viscoelasticity and promote crystallisation of the polymer matrix <sup>109-112</sup>. Other nucleating agents that have been shown to enhance the crystallisation of polyolefins are that of GFs <sup>14</sup>, nanoclay <sup>113</sup> and also 1,3:2,4 bis-O-(4-methylbenzylidene)-D-sorbitol gelling agent (MD) <sup>114</sup>. Wang et al., incorporated 0.2 degree of substitution (DS) of Cellulose Nanofiber (CNF) to isotactic PP. This resulted in the improvement of cellular properties due to the crystallization promotion effect dominating the low expansion ratio foams. However, 0.4 DS of CNF achieved finer cellular structures at higher expansion ratios. This can be attributed to the melt strength domination effect <sup>115</sup>.

Poly(lactic acid) (PLA) is a complex polymer to process due to it having low melt strength and slow crystallisation kinetics <sup>116</sup>. However, it is seen as more environmentally friendly material as it is a biopolymer and biodegradable <sup>117</sup>. Ameli et al., have shown that the addition of 5wt.% of talc to PLA in a MIM process improves the cell density properties, smaller cell size, increased structural uniformity and enhance the mechanical strength <sup>118</sup>. PTFE was added to PLA in a core-back MIM combination by Ishihara et al. The findings concluded that with increased PTFE content, the crystallisation temperature of the PLA increased which enhanced crystallisation and resulting in reduced cell diameters and increased cell density <sup>119</sup>.

Ultrasonic irradiation (UI) can be used to improve the cell density through reduction of the energy barrier during cell nucleation. Such research has only been performed on batch processing but has seen positive results with the cell density <sup>120</sup>. This could expand the materials that could be used for MIM, whereby the cellular structure can be improved during the process without the requirement of costly additives.

## **5.0 Future research**

Microcellular polymer technology needs to be investigated beyond light weight material applications to fulfil the additional product functionality that can be delivered by the technology. For instance, the resulting porous inner core structure of the parts produced through MIM permit the novel inclusion of MWCNT resulting in an electrically conductive part <sup>99</sup>. The authors have identified future research themes which have been illustrated in Figure 9 and explained in further detail in this chapter.

## **insert Figure 9**

**Figure 9** Classification of major MIM future areas of research

### **5.1 Resulting material characterisation**

While some industries are already using the technology <sup>121</sup>, further expansion and reduction in technical uncertainty must be further improved. In particular, the resulting material characteristics must be quantified beyond laboratory-based pilot studies. Also, the fundamentals of the process must be further understood to study the affect that varying process variables have on the resulting cycle time, surface finish improvement and repeatability within an industrial context.

### **5.2 Nano-cellular IM**

Cell coalescence is a problem that occurs during the MIM, especially in nano-cellular IM with the increased cell density, due to a large extensional force rupturing the cell wall. When this process occurs, it causes smaller cells to form together and create larger cells which is a negative process response for creating a homogenous part with a large cell density <sup>122</sup>. MWCNTs have been introduced to metallocene-catalysed copolymer (PEO), with CO<sub>2</sub> in batch processing; which mitigated the cells rupturing and coalescing by aligning the shear and extensional forces <sup>123</sup>.

If nano-cellular parts can be produced through IM and not confined to extrusion or batch processing <sup>124-128</sup>, this offers the potential to replicate membrane technology for filtration system applications. Several research groups have achieved nano-cellular foams with average cell sizes lower than 300nm <sup>129</sup>, or even 200nm <sup>130</sup> by using CO<sub>2</sub> in a batch processing setup <sup>131, 132</sup>. The next step for this research could be to develop the underpinning manufacturing process to satisfy industrial scale-up <sup>133</sup>. The technical challenges are witnessed in the major reduction in residence time from batch processing to MIM, with some experiments requiring over 4 minutes to achieve gas dissolution within the polymer melt <sup>128</sup>.

Nano-cellular technology could be taken even further if the production of membranes <sup>134</sup> could be achieved using nano-cellular injection moulding <sup>131, 132</sup>. If this could be replicated through the injection moulding process then cheap, functional nano-cellular membrane manufacture is possible <sup>124-127</sup>. Wang et al. have shown that porous parts can be produced using the MIM <sup>135</sup>; facilitating novel applications within both membrane manufacture and medical products. Also, nano-cellular parts were produced by Wang et al. in PP with PTFE fibres an in



situ fibrillation technique with MIM and core-back processing <sup>136</sup>. This process shows great potential for the future of this technology.

Graphene, a monolayers of carbon atoms which can built into carbon nano-tubes <sup>137</sup>, is a highly researched material throughout academia and industry <sup>138</sup>. The inclusion of this to the MIM process might not only make the part conductive, like MWCNT, but aid the mechanical properties also. With the research into graphene being extensive, it was only a matter of time before results were shown to include the material in a technology; such as MIM <sup>139</sup>. The revival of polymer-based membranes is promising if functional nano-cellular membranes could be produced through MIM processing <sup>140</sup>.

### **5.3 Advanced applications**

#### **5.3.1 Thermal applications**

The possibility of using the microcellular technology as a form of thermal insulator is a novel application of the technology <sup>141, 142</sup>. In particular, PS foams are typically used to reduce thermal conductivity. Therefore, with the higher density of cells obtainable through MIM insulating properties can be enhanced <sup>1</sup>. Wang et al have developed a mathematical model of thermal transport through nano-cellular polymers <sup>143</sup>. The research concludes that nano-cellular polymers are a super insulating material due to the high infrared absorption capacity and the infrared reflectance on the cell walls <sup>143</sup>. Furthermore, the thermal conductivity was effectively decreased by increasing the refractive index or the absorption coefficient of the polymer matrix <sup>143 144</sup>.

Zhao et al., have produced PP with PTFE fibres foamed parts through high pressure MIM and core-back processing with improved thermal applications <sup>145, 146</sup>. Thermal conductivity as low as  $32.4 \text{ mWm}^{-1}\text{K}^{-1}$  was achieved with the PTFE fibres improving the PP crystallisation and viscoelastic behaviour. The core-back processing promotes an evenly distributed pressure drop throughout the part and thus, fine cells with a high cell density can be produced. Wang et al., have achieved similar thermal properties through the same processing method using high impact polystyrene (HIPS) <sup>147</sup>.

#### **5.3.2 Acoustic applications**

The advances of microcellular technology to be used for acoustic applications has been promising <sup>148, 149</sup>. Ahmed et al. have shown that at higher frequencies, the microcellular parts have increased the sound absorption. Microcellular compression moulding has also been used

to produce PLA parts that show a wider frequency range of sound absorption than normal polymer parts. Modelling the acoustic of these complex parts has also been achieved <sup>148</sup>.

However, in both research studies, MIM was not used and this is the next stage of this technology. Along with the modelling that has been proven by Mosanenzadeh et al., the acoustic applications of MIM will be of benefit for many engineering applications such as automotive parts to reduce the internal noise of the engine <sup>149</sup>. Polyether block amide (PEBA) has foamed using high pressure MIM by Wang et al., and has shown to improve the acoustic properties of the polymer through this technology as the small cells damp the vibrations <sup>150</sup>.

#### **5.4 Modelling**

To escalate the industrial adoption of MIM requires the ability to computational simulate the material performance during product development. Simulation activities are integral to bring components to market quicker. Autodesk and Moldex3D both lead the market with MIM within MoldFlow and Moldex3D respectively <sup>14, 151</sup>. Essentially, to facilitate MIM simulation the cell growth phase of the process requires integration within conventional IM simulation platforms. This additional phase is termed the Classical Nucleation Theory (CNT) <sup>152</sup>. Stress variations and the presence of micro voids also requires consideration whereby the elastic strain energy has a major impact on the nucleation process <sup>153, 154</sup>. Research has demonstrated that approximating the initial cell pressure in the CNT at saturation pressure, leads to major overestimations and therefore inaccurate simulation <sup>155</sup>. Further alterations to the CNT have been developed for heterogenous nucleation occurring at the conical cavities where random apex angles exist on the nucleating agents; with greater contact angles leading to a shorter nucleation onset time <sup>156</sup>.

Pressure rate during the nucleation process is a critical factor to be included in simulation as it facilitates cell formation prediction <sup>157</sup>. Leung et al., have used an altered version of the CNT and also computer simulations, to accurately predict the pressure drop threshold for nucleation of PS <sup>158</sup>. The research showed close alignment to the corresponding empirical experiment work <sup>158</sup>. Xu and Kishbaugh has demonstrated the application of modelling to predict tensile, flexural and impact strength for MIM polymers. The modelling results had less than 10% variation from benchmark moulded test parts. The model utilised a model based on a skin to core structure with the key input parameters being skin thickness and weight reduction from its solid counterpart <sup>159</sup>.

Further modelling could be utilised to inform the prediction of the upper limits of cell density within a microcellular part <sup>160, 161</sup>. Previous research has shown that the CNT does not

provide accurate results and that the self-consistent field theory (SCFT) results in higher accuracy. This improvement in accuracy are due to the calculations assume that the curvature of the cell surface is comparable to that of polymer molecular sizes <sup>162</sup>.

Finally, the modelling of MIM when used in combination with fibres and fillers would assist product development. In particular, the modelling of the cell nucleation when in contact with fibres and fillers. Visualisation work has been performed by Shaayegan et al., whereby PS containing carbon-fibres were modelled. The research concluded that both rotational and translational movements occurred due to the biaxial stretching of the polymer melt in MIM <sup>163</sup>. This research has the potential to be incorporated into computational software to enhance the functionality with regards to resulting fibre orientation.

## 6. Conclusion

This article has provided an explanation of the fundamental stages of MIM process, including recent advances and ongoing research topics. The advanced processing techniques of relevance to MIM are co-injection moulding, core-back processing, gas counter pressure and vario-thermal moulding. The addition of carbon, plasticising agents or nucleating agents have also been investigated. The expand the application of MIM further requires extensive research in the areas of:

- Processing nano-cellular components for membrane applications through IM, not only batch processing and extrusion.
- Improving surface finish defects inherent within the current process.
- Expand the additional functionality of enhancement in acoustic and thermal properties to non-traditional applications.
- Improve the modelling of the technology within industry standard polymer processing software for utilisation during design and process development activities.

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## References

1. Wong A, Guo H, Kumar V, et al. Microcellular Plastics. *Encyclopedia of Polymer Science and Technology* 2016: 1-57. DOI: <https://doi.org/10.1002/0471440264.pst468.pub2>.
2. Stevenson JF. *Innovation in polymer processing: Molding*. Hanser Pun Inc, 1996, p.93-149.
3. Colton JS. *The nucleation of microcellular thermoplastic foam*. PhD Thesis, Massachusetts Institute of Technology, U.S.A, 1985.
4. Kumar V. *Process synthesis for manufacturing microcellular thermoplastic parts : a case study in axiomatic design*. PhD Thesis, Massachusetts Institute of Technology, U.S.A, 1988.
5. Park CB. *The role of polymer/gas solutions in continuous processing of microcellular polymers*. PhD Thesis, Massachusetts Institute of Technology, U.S.A, 1993.
6. Cha SW. *A microcellular foaming/forming process performed at ambient temperature and a super-microcellular foaming process*. PhD Thesis, Massachusetts Institute of Technology, U.S.A, 1994.
7. Baldwin DF. *Microcellular polymer processing and the design of a continuous sheet processing system*. PhD Thesis, Massachusetts Institute of Technology, U.S.A, 1994.
8. Kumar V and Suh NP. A process for making microcellular thermoplastic parts. *Polymer Engineering & Science* 1990; 30: 1323-1329. DOI: 10.1002/pen.760302010.
9. Park CB, Baldwin DF and Suh NP. Axiomatic design of a microcellular filament extrusion system. *Research in Engineering Design* 1996; 8: 166-177. journal article. DOI: 10.1007/bf01608351.
10. Baldwin DF, Park CB and Suh NP. An extrusion system for the processing of microcellular polymer sheets: Shaping and cell growth control. *Polymer Engineering & Science* 1996; 36: 1425-1435. DOI: <https://doi.org/10.1002/pen.10537>.
11. Park CB and Suh NP. Rapid Polymer/Gas Solution Formation for Continuous Production of Microcellular Plastics. *Journal of Manufacturing Science and Engineering* 1996; 118: 639-645. DOI: <https://doi.org/10.1115/1.2831079>.
12. Park CB and Suh NP. Filamentary extrusion of microcellular polymers using a rapid decompressive element. *Polymer Engineering & Science* 1996; 36: 34-48. DOI: 10.1002/pen.10382.
13. Martini-Vvedensky JE, Suh NP and Waldman FA. *Microcellular closed cell foams and their method of manufacture*. Patent 4473665, U.S.A, 1984.
14. Xu J. *Microcellular Injection Molding*. 1 ed. Hoboken, NJ, USA: John Wiley & Sons, Inc., 2010.
15. Xu J and Pierick D. Microcellular foam processing in reciprocating-screw injection molding machines. *Journal of Injection Molding Technology* 2001; 5: 152-159.
16. Pierick DE, Anderson JR, Cha SW, et al. *Injection molding of polymeric material*. Patent 6,884,823 B1, U.S.A, 2005.
17. Goldsberry C. Trexel announces development of new MuCell-focused technical center, <https://www.plasticstoday.com/injection-molding/trexel-announces-development-new-mucell-focused-technical-center/99870300224622> (2016, accessed 8th August 2017).
18. Habibi-Naini S. Optifoam™-The Flexible Solution for Foam Injection Molding. In: *Blowing Agents and Foaming Processes 2004* Hamburg, Germany, 2004, pp.63-74. *Blowing Agents and Foaming Processes*.
19. Błędzki AK, Faruk O, Kirschling H, et al. Microcellular polymers and composites. *Polimery* 2006; 51.

20. Michaeli W, Krumpholz T and Obeloer D. Profoam—A New Foaming Process for Injection Molding. In: *Proceedings of the 66th Annual Technical Conference of the Society of Plastics Engineers*, Milwaukee, WI, U.S.A, 2008, pp.1019-1023. Society of Plastics Engineers.
21. Bryce DM. *Plastic Injection Molding. Material selection and product design fundamentals*. Dearborn, Michigan: Society of Manufacturing Engineers, 1997, p.354.
22. Harper CA and Petrie EM. *Plastics materials and processes: a concise encyclopedia*. Hoboken, NJ, USA: John Wiley & Sons, 2003, p.59.
23. Trexel. TecoCell® - CFA, <http://www.trexel.com/en/tecocell-cfa> (2017, accessed 9th June 2019 2019).
24. Kharbas HA, McNulty JD, Ellingham T, et al. Comparative study of chemical and physical foaming methods for injection-molded thermoplastic polyurethane. *Journal of Cellular Plastics* 2017; 53: 373-388. DOI: 10.1177/0021955x16652107.
25. Bryce DM. *Plastic Injection Molding. Manufacturing process fundamentals*. Dearborn, Michigan: Society of Manufacturing Engineers, 1996, p.253.
26. Broyer E, Gutfinger C and Tadmor Z. A Theoretical Model for the Cavity Filling Process in Injection Molding. *Transactions of the Society of Rheology* 1975; 19: 423-444. DOI: 10.1122/1.549379.
27. Rosato DV, Rosato DV and Rosato MG. *Injection Molding Handbook*. 3rd ed. Massachusetts: Kluwer Academic Publishers, 2000.
28. Goodship V, Arburg Maschinenfabrik Hehl und S and Limited RT. *Practical guide to injection moulding*. 1st ed. Shawbury, Shrewsbury: Rapra Technology Limited, 2004.
29. Lee JWS, Wang J, Yoon JD, et al. Strategies to Achieve a Uniform Cell Structure with a High Void Fraction in Advanced Structural Foam Molding. *Industrial & Engineering Chemistry Research* 2008; 47: 9457-9464. DOI: 10.1021/ie0707016.
30. Llewelyn G, Rees A, Griffiths CA, et al. Advances in Near Net Shape Polymer Manufacturing Through Microcellular Injection Moulding. In: Gupta K (ed) *Near Net Shape Manufacturing Processes*. Cham: Springer International Publishing, 2019, pp.177-189.
31. Lee JWS, Park CB and Kim SG. Reducing Material Costs with Microcellular/Fine-celled Foaming. *Journal of Cellular Plastics* 2007; 43: 297-312. DOI: 10.1177/0021955X07077601.
32. Turng L-S and Kharbas H. Effect of process conditions on the weld-line strength and microstructure of microcellular injection molded parts. *Polymer Engineering & Science* 2003; 43: 157-168. DOI: 10.1002/pen.10013.
33. Shaayegan V, Wang C, Costa F, et al. Effect of the Melt Compressibility and the Pressure Drop Rate on the Cell-Nucleation Behavior in Foam Injection Molding with Mold Opening. *European Polymer Journal* 2017. DOI: 10.1016/j.eurpolymj.2017.05.003.
34. Mark LH, Chu RKM, Wang GL, et al. High-Pressure Preform Foam Blow Molding. *International Polymer Processing* 2017; 32: 637-647. DOI: 10.3139/217.3537.
35. Tromm M, Shaayegan V, Wang C, et al. Investigation of the mold-filling phenomenon in high-pressure foam injection molding and its effects on the cellular structure in expanded foams. *Polymer* 2019; 160: 43-52. DOI: <https://doi.org/10.1016/j.polymer.2018.11.006>.
36. Baldwin DF, Shimbo M and Suh NP. The Role of Gas Dissolution and Induced Crystallization During Microcellular Polymer Processing: A Study of Poly (Ethylene Terephthalate) and Carbon Dioxide Systems. *Journal of Engineering Materials and Technology* 1995; 117: 62-74. DOI: 10.1115/1.2804373.
37. Goel SK and Beckman EJ. Generation of microcellular polymeric foams using supercritical carbon dioxide. I: Effect of pressure and temperature on nucleation. *Polymer Engineering & Science* 1994; 34: 1137-1147. DOI: 10.1002/pen.760341407.

38. Burnham TA, Cha SW, Walat RH, et al. *Method and apparatus for microcellular polymer extrusion*. Patent 6,284,810 B1, USA, 2001.
39. Xu X, Park CB, Lee JWS, et al. Advanced structural foam molding using a continuous polymer/gas melt flow stream. *Journal of Applied Polymer Science* 2008; 109: 2855-2861. DOI: 10.1002/app.28248.
40. Wu X, Ceng H, Cai Y, et al. A single-phase of supercritical CO<sub>2</sub>/ Polystyrene solution in foam extrusion. *Journal of Wuhan University of Technology-Mater Sci Ed* 2008; 23: 804-808. DOI: 10.1007/s11595-007-6804-5.
41. Colton JS and Suh NP. Nucleation of microcellular foam: Theory and practice. *Polymer Engineering & Science* 1987; 27: 500-503. DOI: 10.1002/pen.760270704.
42. Park CB, Baldwin DF and Suh NP. Effect of the pressure drop rate on cell nucleation in continuous processing of microcellular polymers. *Polymer Engineering & Science* 1995; 35: 432-440. DOI: 10.1002/pen.760350509.
43. Kramschuster A, Cavitt R, Ermer D, et al. Quantitative study of shrinkage and warpage behavior for microcellular and conventional injection molding. *Polymer Engineering & Science* 2005; 45: 1408-1418. DOI: 10.1002/pen.20410.
44. McHugh M and Krukoni V. *Supercritical fluid extraction: principles and practice*. 2nd ed. Massachusetts: Butterworth-Heinemann, 2013.
45. Pallay J, Kelemen P, Berghmans H, et al. Expansion of polystyrene using water as the blowing agent. *Macromolecular Materials and Engineering* 2000; 275: 18-25. DOI: 10.1002/(SICI)1439-2054(20000201)275:1<18::AID-MAME18>3.0.CO;2-3.
46. Hilic S, Boyer SAE, Pádua AAH, et al. Simultaneous measurement of the solubility of nitrogen and carbon dioxide in polystyrene and of the associated polymer swelling. *Journal of Polymer Science Part B: Polymer Physics* 2001; 39: 2063-2070. DOI: 10.1002/polb.1181.
47. Yusa A, Yamamoto S, Goto H, et al. A new microcellular foam injection-molding technology using non-supercritical fluid physical blowing agents. *Polymer Engineering & Science* 2017; 57: 105-113. DOI: <https://doi.org/10.1002/pen.24391>.
48. Wang L, Hikima Y, Ohshima M, et al. Unusual Fabrication of Lightweight Injection-Molded Polypropylene Foams by Using Air as the Novel Foaming Agent. *Industrial & Engineering Chemistry Research* 2018; 57: 3800-3804. DOI: 10.1021/acs.iecr.7b05331.
49. Wang L, Hikima Y, Ohshima M, et al. Development of a Simplified Foam Injection Molding Technique and Its Application to the Production of High Void Fraction Polypropylene Foams. *Industrial & Engineering Chemistry Research* 2017; 56: 13734-13742. DOI: 10.1021/acs.iecr.7b03382.
50. Peng J, Turng L-S and Peng X-F. A new microcellular injection molding process for polycarbonate using water as the physical blowing agent. *Polymer Engineering & Science* 2012; 52: 1464-1473. DOI: 10.1002/pen.23092.
51. Cabrera ED, Mulyana R, Castro JM, et al. Pressurized water pellets and supercritical nitrogen in injection molding. *Journal of Applied Polymer Science* 2013; 127: 3760-3767. DOI: 10.1002/app.37652.
52. Doroudiani S, Park CB and Kortschot MT. Processing and characterization of microcellular foamed high-density polyethylene/isotactic polypropylene blends. *Polymer Engineering & Science* 1998; 38: 1205-1215. DOI: <https://doi.org/10.1002/pen.10289>.
53. Shaayegan V, Mark LH, Park CB, et al. Identification of cell-nucleation mechanism in foam injection molding with gas-counter pressure via mold visualization. *AIChE Journal* 2016; 62: 4035-4046. DOI: 10.1002/aic.15433.

54. Shaayegan V, Wang G and Park CB. Effect of foam processing parameters on bubble nucleation and growth dynamics in high-pressure foam injection molding. *Chemical Engineering Science* 2016; 155: 27-37. DOI: 10.1016/j.ces.2016.07.040.
55. Shaayegan V, Wang G and Park CB. Study of the bubble nucleation and growth mechanisms in high-pressure foam injection molding through in-situ visualization. *European Polymer Journal* 2016; 76: 2-13. DOI: <https://doi.org/10.1016/j.eurpolymj.2015.11.021>.
56. Shaayegan V, Mark LH, Tabatabaei A, et al. A new insight into foaming mechanisms in injection molding via a novel visualization mold. *Express Polym Lett* 2016; 10: 462-469. DOI: 10.3144/expresspolymlett.2016.44.
57. Hendry JW. *Method and apparatus for injection molding foamed resin products having a smooth finish on their surface*. Patent 4,201,742, U.S.A, 1980.
58. Brachman AE. *Method of injection molding a structural foamed thermoplastic article having a uniform swirl-free and indent-free surface*. Patent 3940467, USA, 1976.
59. Cha SW and Yoon JD. Label behavior property attached on microcellular foamed parts. *Journal of Applied Polymer Science* 2005; 98: 289-293. DOI: 10.1002/app.21351.
60. Dong G, Zhao G, Guan Y, et al. Formation mechanism and structural characteristics of unfoamed skin layer in microcellular injection-molded parts. *Journal of Cellular Plastics* 2016; 52: 419-439. DOI: 10.1177/0021955x15577149.
61. Coyle DJ, Blake JW and Macosko CW. The kinematics of fountain flow in mold-filling. *AIChE Journal* 1987; 33: 1168-1177. DOI: 10.1002/aic.690330711.
62. Baltussen MGHM, Hulsen MA and Peters GWM. Numerical simulation of the fountain flow instability in injection molding. *Journal of Non-Newtonian Fluid Mechanics* 2010; 165: 631-640. DOI: <https://doi.org/10.1016/j.jnnfm.2010.03.001>.
63. Lee J, Turng L-S, Dougherty E, et al. A novel method for improving the surface quality of microcellular injection molded parts. *Polymer* 2011; 52: 1436-1446. DOI: <https://doi.org/10.1016/j.polymer.2011.01.026>
64. Shimbo M, Baldwin DF and Suh NP. The viscoelastic behavior of microcellular plastics with varying cell size. *Polymer Engineering & Science* 1995; 35: 1387-1393. DOI: 10.1002/pen.760351710.
65. Bledzki AK, Kirschling H, Rohleder M, et al. Correlation between injection moulding processing parameters and mechanical properties of microcellular polycarbonate. *Journal of Cellular Plastics* 2012; 48: 301-340. DOI: doi:10.1177/0021955X12441193.
66. Gómez-Monterde J, Schulte M, Ilijevic S, et al. Effect of microcellular foaming on the fracture behavior of ABS polymer. *Journal of Applied Polymer Science* 2016; 133: 1-10. DOI: 10.1002/app.43010.
67. Goel SK and Beckman EJ. Generation of microcellular polymeric foams using supercritical carbon dioxide. II: Cell growth and skin formation. *Polymer Engineering & Science* 1994; 34: 1148-1156. DOI: 10.1002/pen.760341408.
68. Advanced|CAE|Technology. C-MOLD Co-Injection, [http://www.dc.engr.scu.edu/cmdoc/fp\\_doc/f5co1.frm.html](http://www.dc.engr.scu.edu/cmdoc/fp_doc/f5co1.frm.html) (1996, accessed 10th July 2017).
69. Turng LS and Kharbas H. Development of a Hybrid Solid-Microcellular Co-injection Molding Process. *International Polymer Processing* 2004; 19: 77-86. DOI: <https://doi.org/10.3139/217.1806>.
70. Reglero Ruiz JA, Vincent M, Agassant J-F, et al. Morphological analysis of microcellular PP produced in a core-back injection process using chemical blowing agents and gas counter pressure. *Polymer Engineering & Science* 2015; 55: 2465-2473. DOI: 10.1002/pen.24136.



71. Ishikawa T and Ohshima M. Visual observation and numerical studies of polymer foaming behavior of polypropylene/carbon dioxide system in a core-back injection molding process. *Polymer Engineering & Science* 2011; 51: 1617-1625. DOI: 10.1002/pen.21945.
72. Wang L, Ishihara S, Ando M, et al. Fabrication of High Expansion Microcellular Injection-Molded Polypropylene Foams by Adding Long-Chain Branches. *Industrial & Engineering Chemistry Research* 2016; 55: 11970-11982. DOI: 10.1021/acs.iecr.6b03641.
73. Wang L, Ando M, Kubota M, et al. Effects of hydrophobic-modified cellulose nanofibers (CNFs) on cell morphology and mechanical properties of high void fraction polypropylene nanocomposite foams. *Composites Part A: Applied Science and Manufacturing* 2017; 98: 166-173. DOI: <https://doi.org/10.1016/j.compositesa.2017.03.028>.
74. Wang L, Ishihara S, Hikima Y, et al. Unprecedented Development of Ultrahigh Expansion Injection-Molded Polypropylene Foams by Introducing Hydrophobic-Modified Cellulose Nanofibers. *ACS Applied Materials & Interfaces* 2017; 9: 9250-9254. DOI: 10.1021/acsami.7b01329.
75. Ishikawa T, Taki K and Ohshima M. Visual observation and numerical studies of N<sub>2</sub> vs. CO<sub>2</sub> foaming behavior in core-back foam injection molding. *Polymer Engineering & Science* 2012; 52: 875-883. DOI: 10.1002/pen.22154.
76. Shutov FA, Henrici-Olivé G and Olivé S. Injection Molding: Gas Counter Pressure Process. In: Henrici-Olivé G and Olivé S (eds) *Integral/Structural Polymer Foams: Technology, Properties and Applications*. Berlin, Heidelberg: Springer Berlin Heidelberg, 1986, pp.71-80.
77. Bledzki AK, Kirschling H, Steinbichler G, et al. Polycarbonate Microfoams with a Smooth Surface and Higher Notched Impact Strength. *Journal of Cellular Plastics* 2004; 40: 489-496. DOI: doi:10.1177/0021955X04048423.
78. Bledzki AK, Rohleder M, Kirschling H, et al. Microcellular Polycarbonate with Improved Notched Impact Strength Produced by Injection Moulding with Physical Blowing Agent. *Cellular Polymers* 2008; 27: 327-345.
79. Chen S-C, Hsu P-S and Hwang S-S. The effects of gas counter pressure and mold temperature variation on the surface quality and morphology of the microcellular polystyrene foams. *Journal of Applied Polymer Science* 2013; 127: 4769-4776. DOI: 10.1002/app.37994.
80. Chen SC, Hsu PS and Lin YW. Establishment of Gas Counter Pressure Technology and Its Application to Improve the Surface Quality of Microcellular Injection Molded Parts. *International Polymer Processing* 2011; 26: 275-282. DOI: 10.3139/217.2437.
81. Lee JWS, Lee RE, Wang J, et al. Study of the foaming mechanisms associated with gas counter pressure and mold opening using the pressure profiles. *Chemical Engineering Science* 2017; 167: 105-119. DOI: <https://doi.org/10.1016/j.ces.2017.04.005>.
82. Bryce DM. *Plastic Injection Molding. Mold design and construction fundamentals*. Dearborn, Michigan: Society of Manufacturing Engineers, 1998, p.182.
83. Smith C. MuCell gloss breakthrough set to double Trexel's sales, [http://www.trexel.com/news-events-awards/news-pdfs/oct04\\_b.pdf](http://www.trexel.com/news-events-awards/news-pdfs/oct04_b.pdf) (2004, accessed 19th June 2017).
84. Xiao C-L, Huang H-X and Yang X. Development and application of rapid thermal cycling molding with electric heating for improving surface quality of microcellular injection molded parts. *Applied Thermal Engineering* 2016; 100: 478-489. DOI: 10.1016/j.applthermaleng.2016.02.045.
85. Chen S-C, Lin Y-W, Chien R-D, et al. Variable mold temperature to improve surface quality of microcellular injection molded parts using induction heating technology. *Advances in Polymer Technology* 2008; 27: 224-232. DOI: 10.1002/adv.20133.

86. Hopmann C, Lammert N and Zhang Y. Improvement of foamed part surface quality with variothermal temperature control and analysis of the mechanical properties. *Journal of Cellular Plastics* 2019; 0: 0021955X19841050. DOI: <https://doi.org/10.1177%2F0021955X19841050>.
87. Lee J and Turng L-S. Improving surface quality of microcellular injection molded parts through mold surface temperature manipulation with thin film insulation. *Polymer Engineering & Science* 2010; 50: 1281-1289. DOI: 10.1002/pen.21658.
88. Chen S-C, Li H-M, Hwang S-S, et al. Passive mold temperature control by a hybrid filming-microcellular injection molding processing. *International Communications in Heat and Mass Transfer* 2008; 35: 822-827. DOI: 10.1016/j.icheatmasstransfer.2008.03.013.
89. Guo W, Yang Q, Mao H, et al. A Combined In-Mold Decoration and Microcellular Injection Molding Method for Preparing Foamed Products with Improved Surface Appearance. *Polymers* 2019; 11: 778. DOI: <https://doi.org/10.3390/polym11050778>.
90. Bryce DM. *Plastic Injection Molding. Manufacturing startup and management*. Dearborn, Michigan: Society of Manufacturing Engineers, 1999, p.192.
91. Xi Z, Sha X, Liu T, et al. Microcellular injection molding of polypropylene and glass fiber composites with supercritical nitrogen. *Journal of Cellular Plastics* 2014; 50: 489-505. DOI: 10.1177/0021955X14528931.
92. Ameli A, Nofar M, Wang S, et al. Lightweight Polypropylene/Stainless-Steel Fiber Composite Foams with Low Percolation for Efficient Electromagnetic Interference Shielding. *ACS Applied Materials & Interfaces* 2014; 6: 11091-11100. DOI: 10.1021/am500445g.
93. Ding W, Jahani D, Chang E, et al. Development of PLA/cellulosic fiber composite foams using injection molding: Crystallization and foaming behaviors. *Composites Part A: Applied Science and Manufacturing* 2016; 83: 130-139. DOI: 10.1016/j.compositesa.2015.10.003.
94. Wong S, Lee JWS, Naguib HE, et al. Effect of Processing Parameters on the Mechanical Properties of Injection Molded Thermoplastic Polyolefin (TPO) Cellular Foams. *Macromolecular Materials and Engineering* 2008; 293: 605-613. DOI: 10.1002/mame.200700362.
95. Xin ZX, Zhang ZX, Pal K, et al. Study of microcellular injection-molded polypropylene/waste ground rubber tire powder blend. *Materials & Design* 2010; 31: 589-593. DOI: <https://doi.org/10.1016/j.matdes.2009.07.002>.
96. Zhang P, Zhou NQ, Wu QF, et al. Microcellular foaming of PE/PP blends. *Journal of Applied Polymer Science* 2007; 104: 4149-4159. DOI: 10.1002/app.26071.
97. Kharbas HA, Ellingham T, Manitiu M, et al. Effect of a cross-linking agent on the foamability of microcellular injection molded thermoplastic polyurethane. *Journal of Cellular Plastics* 2017; 53: 407-423. DOI: 10.1177/0021955x16652109.
98. Li J, Chen Z, Wang X, et al. Cell morphology and mechanical properties of microcellular mucell® injection molded polyetherimide and polyetherimide/fillers composite foams. *Journal of Applied Polymer Science* 2013; 130: 4171-4181. DOI: 10.1002/app.39698.
99. Ameli A, Kazemi Y, Wang S, et al. Process-microstructure-electrical conductivity relationships in injection-molded polypropylene/carbon nanotube nanocomposite foams. *Composites Part A: Applied Science and Manufacturing* 2017; 96: 28-36. DOI: 10.1016/j.compositesa.2017.02.012.
100. Wang G, Zhao G, Wang S, et al. Injection-molded microcellular PLA/graphite nanocomposites with dramatically enhanced mechanical and electrical properties for ultra-efficient EMI shielding applications. *Journal of Materials Chemistry C* 2018; 6: 6847-6859. DOI: 10.1039/C8TC01326H.

101. Alessi P, Cortesi A, Kikic I, et al. Plasticization of polymers with supercritical carbon dioxide: Experimental determination of glass-transition temperatures. *Journal of Applied Polymer Science* 2003; 88: 2189-2193. DOI: 10.1002/app.11881.
102. Li YG and Park CB. Effects of Branching on the Pressure–Volume–Temperature Behaviors of PP/CO<sub>2</sub> Solutions. *Industrial & Engineering Chemistry Research* 2009; 48: 6633-6640. DOI: 10.1021/ie8015279.
103. Li YG, Park CB, Li HB, et al. Measurement of the PVT property of PP/CO<sub>2</sub> solution. *Fluid Phase Equilibria* 2008; 270: 15-22. DOI: 10.1016/j.fluid.2008.05.007.
104. Li YG, Mahmood SH and Park CB. Visualization for measuring the PVT property of viscoelastic polystyrene/CO<sub>2</sub> mixtures at elevated temperatures and pressures. *Polymer Testing* 2016; 55: 88-96. DOI: 10.1016/j.polymer.2016.08.010.
105. von Konigslow K, Park CB and Thompson RB. Evaluating Characteristic Parameters for Carbon Dioxide in the Sanchez–Lacombe Equation of State. *Journal of Chemical & Engineering Data* 2017; 62: 585-595. DOI: 10.1021/acs.jced.6b00743.
106. Mahmood SH, Xin CL, Gong P, et al. Dimethyl ether's plasticizing effect on carbon dioxide solubility in polystyrene. *Polymer* 2016; 97: 95-103. DOI: 10.1016/j.polymer.2016.05.018.
107. Premalal HGB, Ismail H and Baharin A. Comparison of the mechanical properties of rice husk powder filled polypropylene composites with talc filled polypropylene composites. *Polymer Testing* 2002; 21: 833-839. DOI: [https://doi.org/10.1016/S0142-9418\(02\)00018-1](https://doi.org/10.1016/S0142-9418(02)00018-1).
108. Kaltenecker-Uray A, Rieß G, Lucyshyn T, et al. Physical Foaming and Crosslinking of Polyethylene with Modified Talcum. *Polymers* 2019; 11: 1472. DOI: <https://doi.org/10.3390/polym11091472>.
109. Naguib HE, Park CB and Lee PC. Effect of Talc Content on the Volume Expansion Ratio of Extruded PP Foams. *Journal of Cellular Plastics* 2003; 39: 499-511. DOI: 10.1177/0021955X03039247.
110. Kim SG, Lee JWS, Park CB, et al. Enhancing cell nucleation of thermoplastic polyolefin foam blown with nitrogen. *Journal of Applied Polymer Science* 2010; 118: 1691-1703. DOI: 10.1002/app.32294.
111. Wang G, Zhao G, Dong G, et al. Lightweight and strong microcellular injection molded PP/talc nanocomposite. *Composites Science and Technology* 2018; 168: 38-46. DOI: <https://doi.org/10.1016/j.compscitech.2018.09.009>.
112. Llewelyn G, Rees A, Griffiths CA, et al. A Novel Hybrid Foaming Method for Low-Pressure Microcellular Foam Production of Unfilled and Talc-Filled Copolymer Polypropylenes. *Polymers* 2019; 11: 1896. DOI: <https://doi.org/10.3390/polym11111896>.
113. Ameli A, Nofar M, Jahani D, et al. Development of high void fraction polylactide composite foams using injection molding: Crystallization and foaming behaviors. *Chemical Engineering Journal* 2015; 262: 78-87. DOI: 10.1016/j.cej.2014.09.087.
114. Wang L, Hikima Y, Ishihara S, et al. Fabrication of lightweight microcellular foams in injection-molded polypropylene using the synergy of long-chain branches and crystal nucleating agents. *Polymer* 2017; 128: 119-127. DOI: <https://doi.org/10.1016/j.polymer.2017.09.025>.
115. Wang L, Okada K, Hikima Y, et al. Effect of Cellulose Nanofiber (CNF) Surface Treatment on Cellular Structures and Mechanical Properties of Polypropylene/CNF Nanocomposite Foams via Core-Back Foam Injection Molding. *Polymers* 2019; 11: 249. DOI: <https://doi.org/10.3390/polym11020249>.

116. Volpe V and Pantani R. Effect of processing condition on properties of polylactic acid parts obtained by foam injection molding. *Journal of Cellular Plastics* 2017; 53: 491-502. DOI: 10.1177/0021955x16670589.
117. Nofar M and Park CB. Poly (lactic acid) foaming. *Progress in Polymer Science* 2014; 39: 1721-1741. DOI: 10.1016/j.progpolymsci.2014.04.001.
118. Ameli A, Jahani D, Nofar M, et al. Processing and characterization of solid and foamed injection-molded polylactide with talc. *Journal of Cellular Plastics* 2013; 49: 351-374. DOI: 10.1177/0021955X13481993.
119. Ishihara S, Hikima Y and Ohshima M. Preparation of open microcellular polylactic acid foams with a microfibrillar additive using coreback foam injection molding processes. *Journal of Cellular Plastics* 2018; 54: 765-784. DOI: 10.1177/0021955x18770441.
120. Wang J, Zhai W, Ling J, et al. Ultrasonic Irradiation Enhanced Cell Nucleation in Microcellular Poly(lactic Acid): A Novel Approach to Reduce Cell Size Distribution and Increase Foam Expansion. *Industrial & Engineering Chemistry Research* 2011; 50: 13840-13847. DOI: 10.1021/ie201643j.
121. Romeo A. Microcellular Injection Moulding. In: *Summer School, New trends in plastic engineering* (ed Trexel Inc), Bellignat, France, 9th September 2013, Proplast.
122. Guo M-C, Heuzey M-C and Carreau PJ. Cell structure and dynamic properties of injection molded polypropylene foams. *Polymer Engineering & Science* 2007; 47: 1070-1081. DOI: 10.1002/pen.20786.
123. Zhai W, Wang J, Chen N, et al. The orientation of carbon nanotubes in poly(ethylene-co-octene) microcellular foaming and its suppression effect on cell coalescence. *Polymer Engineering & Science* 2012; 52: 2078-2089. DOI: 10.1002/pen.23157.
124. Wang G, Zhao J, Mark LH, et al. Ultra-tough and super thermal-insulation nanocellular PMMA/TPU. *Chemical Engineering Journal* 2017; 325: 632-646. DOI: <https://doi.org/10.1016/j.cej.2017.05.116>.
125. Nofar M, Ameli A and Park CB. A novel technology to manufacture biodegradable polylactide bead foam products. *Materials & Design* 2015; 83: 413-421. DOI: <https://doi.org/10.1016/j.matdes.2015.06.052>.
126. Saniei M, Tran M-P, Bae S-S, et al. From micro/nano structured isotactic polypropylene to a multifunctional low-density nanoporous medium. *RSC Advances* 2016; 6: 108056-108066. DOI: 10.1039/C6RA22607H.
127. Nofar M, Ameli A and Park CB. Development of polylactide bead foams with double crystal melting peaks. *Polymer* 2015; 69: 83-94. DOI: <https://doi.org/10.1016/j.polymer.2015.05.048>.
128. Bernardo V, Martin-de Leon J, Pinto J, et al. Low-density PMMA/MAM nanocellular polymers using low MAM contents: Production and characterization. *Polymer* 2019; 163: 115-124. DOI: <https://doi.org/10.1016/j.polymer.2018.12.057>.
129. Fujimoto Y, Ray SS, Okamoto M, et al. Well-Controlled Biodegradable Nanocomposite Foams: From Microcellular to Nanocellular. *Macromolecular Rapid Communications* 2003; 24: 457-461. DOI: 10.1002/marc.200390068.
130. Martín-de León J, Bernardo V and Rodríguez-Pérez M<sup>Á</sup>. Nanocellular Polymers: The Challenge of Creating Cells in the Nanoscale. *Materials* 2019; 12: 797. DOI: <https://doi.org/10.3390/ma12050797>.
131. Cherukupally P, Acosta EJ, Hinestroza JP, et al. Acid-Base Polymeric Foams for the Adsorption of Micro-oil Droplets from Industrial Effluents. *Environmental Science & Technology* 2017; 51: 8552-8560. DOI: 10.1021/acs.est.7b01255.

132. Costeux S, Zhu L, Weikart CM, et al. *Nanoporous polymeric foam having high porosity* Patent 9718938 B2, U.S.A, 2017.
133. Costeux S. CO<sub>2</sub>-blown nanocellular foams. *Journal of Applied Polymer Science* 2014; 131. DOI: 10.1002/app.41293.
134. Price A, Gillen T, Liu C, et al. Evaluation of porous membrane core elasticity and porous morphology for polypyrrole trilayer actuators. *Journal of Cellular Plastics* 2012; 48: 25-42. DOI: 10.1177/0021955x11420187.
135. Wang X, Salick MR, Gao Y, et al. Interconnected porous poly( $\epsilon$ -caprolactone) tissue engineering scaffolds fabricated by microcellular injection molding. *Journal of Cellular Plastics* 2018; 54: 379-397. DOI: 10.1177/0021955x16681470.
136. Wang G, Zhao G, Zhang L, et al. Lightweight and tough nanocellular PP/PTFE nanocomposite foams with defect-free surfaces obtained using in situ nanofibrillation and nanocellular injection molding. *Chemical Engineering Journal* 2018; 350: 1-11. DOI: <https://doi.org/10.1016/j.cej.2018.05.161>.
137. Geim AK and Novoselov KS. The rise of graphene. *Nature Materials* 2007; 6: 183. DOI: 10.1038/nmat1849.
138. Geim AK. Graphene: Status and Prospects. *Science* 2009; 324: 1530-1534. DOI: 10.1126/science.1158877.
139. Pedros J, Bosca A, Martinez J, et al. *Hierachial compostie structures based on graphene foam or graphene-like foam*. Patent 20170237075, U.S.A, 2017.
140. Vlasiouk IV. A scalable graphene-based membrane. *Nature Nanotechnology* 2017; 12: 1022. DOI: 10.1038/nnano.2017.184.
141. Gong P, Buahom P, Tran M-P, et al. Heat transfer in microcellular polystyrene/multi-walled carbon nanotube nanocomposite foams. *Carbon* 2015; 93: 819-829. DOI: 10.1016/j.carbon.2015.06.003.
142. Grignard B, Thomassin JM, Gennen S, et al. CO<sub>2</sub>-blown microcellular non-isocyanate polyurethane (NIPU) foams: from bio- and CO<sub>2</sub>-sourced monomers to potentially thermal insulating materials. *Green Chemistry* 2016; 18: 2206-2215. DOI: 10.1039/C5GC02723C.
143. Wang G, Wang C, Zhao J, et al. Modelling of thermal transport through a nanocellular polymer foam: toward the generation of a new superinsulating material. *Nanoscale* 2017; 9: 5996-6009. DOI: 10.1039/C7NR00327G. DOI: 10.1039/C7NR00327G.
144. Gong P, Wang G, Tran M-P, et al. Advanced bimodal polystyrene/multi-walled carbon nanotube nanocomposite foams for thermal insulation. *Carbon* 2017; 120: 1-10. DOI: 10.1016/j.carbon.2017.05.029.
145. Zhao J, Zhao Q, Wang C, et al. High thermal insulation and compressive strength polypropylene foams fabricated by high-pressure foam injection molding and mold opening of nano-fibrillar composites. *Materials & Design* 2017; 131: 1-11. DOI: <https://doi.org/10.1016/j.matdes.2017.05.093>.
146. Zhao J, Zhao Q, Wang L, et al. Development of high thermal insulation and compressive strength BPP foams using mold-opening foam injection molding with in-situ fibrillated PTFE fibers. *European Polymer Journal* 2018; 98: 1-10. DOI: <https://doi.org/10.1016/j.eurpolymj.2017.11.001>.
147. Wang G, Zhao G, Dong G, et al. Lightweight, thermally insulating, and low dielectric microcellular high-impact polystyrene (HIPS) foams fabricated by high-pressure foam injection molding with mold opening. *Journal of Materials Chemistry C* 2018; 6: 12294-12305. DOI: 10.1039/C8TC04248A. DOI: 10.1039/C8TC04248A.

148. Ahmed MYS, Wang C, Park CB, et al. Microcellular Ceramic Foams: Manufacturing and Study of Acoustical Properties. *SAE Technical Paper 2007-01-2187*. 2007.
149. Mosanenzadeh SG, Naguib HE, Park CB, et al. Development, characterization, and modeling of environmentally friendly open-cell acoustic foams. *Polymer Engineering & Science* 2013; 53: 1979-1989. DOI: 10.1002/pen.23443.
150. Wang G, Zhao G, Dong G, et al. Lightweight, super-elastic, and thermal-sound insulation bio-based PEBA foams fabricated by high-pressure foam injection molding with mold-opening. *European Polymer Journal* 2018; 103: 68-79. DOI: <https://doi.org/10.1016/j.eurpolymj.2018.04.002>.
151. Moldex3D. Accurate simulation results on MuCell Technology enables adoption of Moldex3D solution, <http://www.moldex3d.com/en/assets/2014/10/Custom-Success-Proplast.pdf> (2014, accessed 6th December 2017).
152. Lutsko JF and Durán-Olivencia MA. Classical nucleation theory from a dynamical approach to nucleation. *The Journal of Chemical Physics* 2013; 138: 244908. DOI: 10.1063/1.4811490.
153. Wong A, Wijnands SFL, Kuboki T, et al. Mechanisms of nanoclay-enhanced plastic foaming processes: effects of nanoclay intercalation and exfoliation. *Journal of Nanoparticle Research* 2013; 15: 1815. journal article. DOI: 10.1007/s11051-013-1815-y.
154. Wang G, Zhao J, Yu K, et al. Role of elastic strain energy in cell nucleation of polymer foaming and its application for fabricating sub-microcellular TPU microfilms. *Polymer* 2017; 119: 28-39. DOI: <https://doi.org/10.1016/j.polymer.2017.05.016>.
155. Leung SN, Li H and Park CB. Impact of approximating the initial bubble pressure on cell nucleation in polymeric foaming processes. *Journal of Applied Polymer Science* 2007; 104: 902-908. DOI: 10.1002/app.25728.
156. LI SNLCBPH. Numerical simulation of polymeric foaming processes using modified nucleation theory. *Plastics, Rubber and Composites* 2006; 35: 93-100. DOI: 10.1179/174328906X103079.
157. Wang C, Leung SN, Bussmann M, et al. Numerical Investigation of Nucleating-Agent-Enhanced Heterogeneous Nucleation. *Industrial & Engineering Chemistry Research* 2010; 49: 12783-12792. DOI: 10.1021/ie1017207.
158. Leung SN, Wong A, Park CB, et al. Strategies To Estimate the Pressure Drop Threshold of Nucleation for Polystyrene Foam with Carbon Dioxide. *Industrial & Engineering Chemistry Research* 2009; 48: 1921-1927. DOI: 10.1021/ie800079x.
159. Xu J and Kishbaugh L. Simple Modeling of the Mechanical Properties with Part Weight Reduction for Microcellular Foam Plastic. *Journal of Cellular Plastics* 2003; 39: 29-47. DOI: <https://doi.org/10.1177%2F002195503031480>.
160. Kim Y, Park CB, Chen P, et al. Maximal cell density predictions for compressible polymer foams. *Polymer* 2013; 54: 841-845. DOI: 10.1016/j.polymer.2012.11.067.
161. Kim Y, Park CB, Chen P, et al. Towards maximal cell density predictions for polymeric foams. *Polymer* 2011; 52: 5622-5629. DOI: 10.1016/j.polymer.2011.09.046.
162. Kim Y, Park CB, Chen P, et al. Origins of the failure of classical nucleation theory for nanocellular polymer foams. *Soft Matter* 2011; 7: 7351-7358. DOI: 10.1039/C1SM05575E.
163. Shaayegan V, Ameli A, Wang S, et al. Experimental observation and modeling of fiber rotation and translation during foam injection molding of polymer composites. *Composites Part A: Applied Science and Manufacturing* 2016; 88: 67-74. DOI: <https://doi.org/10.1016/j.compositesa.2016.05.013>.

