

Advances in Microcellular Injection Moulding

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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 Program¹. 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 products². The initial publications and thesis' from this research institute discovered the proof of concept and advanced the fundamental theories behind the technology³⁻¹². This pioneering proof of concept work focused on batch processing and extrusion with the first U.S. patent being issued in 1984¹³. The first commercial activity followed in 1998 when Axiomatics Corp., known today as Trexel Inc., built the first reciprocating screw microcellular injection moulding (MIM) machine¹⁴⁻¹⁶.

MuCell®, Trexel's patented MIM technology, was established in 2000¹⁴ and they partnered with major injection moulding (IM) companies¹⁷. Other MIM technologies are available; Optifoam®, Ergocell® and ProFoam® which all use variations of MuCell®¹⁸⁻²⁰.

Prior to the development of microcellular technology, conventional foam was used to produce polymer parts with cellular structure²¹. Moreover, this technology is limited to cell densities is much lower than that obtainable from MIM and with poor mechanical properties¹⁴. However, MIM creates parts that has reduced polymer content, lower final part weight and processing energy requirements¹⁵. 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 polymer²². CBAs used are ammonium, sodium bicarbonate or complex inert gas-releasing materials^{21,23} and typically produce final parts with lower cell densities and larger average cell size²⁴.

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 ²⁵. This process can be divided into three key stages: plastication (polymer granules converted to molten phase ²⁵), mould filling (molten polymer forced into a mould, including compensation for shrinkage ²⁶) and cooling (where this molten polymer cools inside the mould ²⁷) ²⁸. 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 ²⁹.

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) ³⁰

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 ¹⁴. This is beneficial as the price of raw materials for the polymer has increased dramatically in recent years ³¹.

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 ¹⁴. 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 ¹⁴. Also, the mechanical properties of the underpinning process tooling can be reduced to reflect the reduction in both injection pressure and clamp tonnage ¹⁴. In low-pressure foaming, no packing and holding is required in the MIM process; this is performed by cell nucleation and expansion ³². 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 cooling³³⁻³⁵.

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 mould¹⁵. Figure 2 provides a schematic of the stages.

insert Figure 2

Figure 2 Microcellular foaming process¹

2.3.1 SCF mixing and dissolution

When processing with MIM, SCF is injected into the barrel in order to generate gas-polymer solution³⁶. 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 temperature³⁷. 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 diameter¹⁴.

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 force². 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^{14, 38, 39}. This single-phase solution is critical in obtaining strong, consistent parts and is the most challenging element of the technology⁴⁰.

2.3.2 Cell nucleation

Cell nucleation can be either homogenous or heterogeneous. Both need to be induced by a rapid thermodynamic instability⁴¹: 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 equation⁴². 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 drops¹⁴.

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 grow¹⁴.

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 walls¹⁴.

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 factors⁴³.

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 highlighted⁴⁴.

insert Figure 3

Figure 3 Pressure-Temperature graph phases for gas⁴²

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 (N₂) and Carbon Dioxide (CO₂) are: -147.0 °C and 31.1 °C for T_{cr} and 3.4 MPa and 7.22 MPa for P_{cr} respectively ^{2,6}.

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 ^{14, 45}. Therefore, for the application of MIM, N₂ and CO₂ 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 ^{14, 46}. N₂ has proven to achieve lower solubility within the molten polymer when compared to CO₂ ⁴⁶.

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 N₂ and CO₂ at lower pressures than the Super Critical (SC) state ⁴⁷. 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 N₂ and CO₂ respectively. An additional venting system was also added to allow for excess gas evacuation when the maximum solubility level was reached ⁴⁷. 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 N₂ and CO₂ as the SCFs ⁴⁸. Cell diameters of 7 um and cell density of 1.63x10⁹ cells/cm³ were achieved ^{48, 49}.

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 ⁵⁰. . 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 ⁵⁰.

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 barrel⁵¹. 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 μm ⁵¹.

2.5 Cell structure

Microcellular foaming processes produce significantly smaller cell structures than regular foaming produced by CBAs⁵². In particular, the smallest cell structure achieved through CBA is 250 μm . Typically, microcellular foaming produces cells in the range of 3-100 μm ¹⁴. Figure 4 illustrates a typical part structure processed with MuCell® IM.

insert Figure 4

Figure 4 MuCell® processed PP-Talc part with N₂ 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 CO₂ were used⁵³⁻⁵⁶. 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 structure⁵⁴.

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^{57,58}. 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 process¹⁴.

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 ^{59, 60}. 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 ⁶¹. 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 ¹⁶.

insert Figure 5

Figure 5 Fountain flow with (a) advancement of the skin layer and (b) the increase and formation of the skin layer ⁶²

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 ⁶³. This was achieved by using low density polyethylene (LDPE) and polypropylene (PP) with a N₂ content of 0.173% or less ⁶³. The research demonstrates that when smaller concentrations of N₂ are used, there is a reduction in supersaturation which results in surface defect free parts with a weight saving of up to 8% ⁶³.

3.2 Weld line strength

Turng et al. have investigated the effect of process parameters on weld line formation within products produced through MIM ³². 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 ³².

3.2 Alteration of the mechanical properties

The resulting mechanical strength of components produced through MIM plays a significant role to expand their applications ^{64, 65}. Gomez-Monterde et al., investigated using MuCell® in combination with a Acrylonitrile Butadiene Styrene (ABS) component ⁶⁶. 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 ⁶⁶.

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 ⁶⁷. 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 ⁶⁸.

Turng and Kharbas have shown that co-injection moulding technology can be used in combination with MIM ⁶⁹. Cells of 8-12 μm 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 ⁶⁹.

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 ⁷⁰. 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 ⁷¹. This technique achieves high expansion foam due to the mould cavity suddenly increasing and thus, decreasing the melt pressure ⁷². Void fractions as high as 80% have been achieved in MIM with core-back processing for the manufacture of ultra-light weight components ^{73, 74}.

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 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 ³³.

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.) ³³

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 ⁷⁵.

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

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 ⁷⁶.

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 μm to 0.85 μm ⁷⁷. The investigation also concluded that an improvement in tensile and impact strength was witnessed ⁷⁷. 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 μm 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 ⁷⁸. Both studies also showed an improvement in the resulting toughness when compared to conventional IM ⁷⁸.

Chen et al., investigated the effects of GCP and mould temperature on the resulting surface quality and cellular morphology when using the MuCell® process ⁷⁹. 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 ⁷⁹. 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 ⁷⁹.

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 ⁸⁰. Furthermore, it was found that when applying a holding time of 10 seconds, the parts exhibited no foaming until the melt is solidified ⁸⁰.

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 ⁸¹. 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 ⁸¹.

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 ^{82, 83}. 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 ⁸⁴. 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 ⁸⁴.

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

from 100 °C to 160 °C⁸⁵. This decreased the surface roughness of PC from 25µm to 6.5µm⁸⁵. 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 further⁸⁵. 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 interface⁸⁵.

insert Figure 7

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

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 blend⁸⁶. 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 MIM⁸⁶.

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 coating⁸⁷. 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 marks⁸⁷.

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.)⁸⁷

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 insulator⁸⁷. In this case, polytetrafluoroethylene (PTFE) was added to the mould wall before the MIM process. It

was shown that a 175 μm PTFE layer was sufficient to keep the interfacial temperature above the crystallisation temperature of LDPE⁸⁷. Also, the surface roughness of the parts produced in this research were reduced⁸⁷.

Similar research was performed by Chen et al.⁸⁸. In the research, PC was used in MIM with a polyethylene terephthalate (PET) mould insulator⁸⁸. The surface roughness of the final parts was reduced drastically with the integration of the a 0.125 μm PET film. In particular, the surface roughness decrease from 26 μm down to 5.6 μm ⁸⁸. With a 0.188 mm film, the surface roughness was further reduced to 1.8 μm , giving a 93% improvement from the standard microcellular injected moulded part⁸⁸. 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 constant⁸⁹.

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 shrinkage⁹⁰. Xi et al., have shown that glass fibres (GF) can be added to MIM to achieve better mechanical strength⁹¹. 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 orientation⁹².

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 strength⁹³. Xin et al., have researched a novel filler of waste ground rubber tire (WGRT) to PP, forming thermoplastic polyolefin (TPO)⁹⁴. The research concluded that for the application of MIM the addition of WGRT to the PP results in enhanced formation of the cell structure⁹⁵.

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 structure⁹⁶. The research concluded that for all of the PP/PE blends, the melt strength was initially enhanced until a PE content of 30% was achieved⁹⁶.

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 process⁹⁷.

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 ⁹⁸.

MWCNT have also been added to PP during the MIM process by Ameli et al., to demonstrate how this process can produce conductive components ⁹⁹. 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 ⁹⁹. The research concluded that a 30% weight reduction and six times greater electrical conductivity can be obtained when compared to conventional IM ⁹⁹.

Wang et al., have used PLA/graphite nanocomposites in MIM with core-back processing for EMI shielding applications ¹⁰⁰. 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 ¹⁰⁰.

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 ¹⁰¹. 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 ^{102, 103}. In general, volume swelling increases with increased pressure or by decreased temperature of the polymer/gas solution in MIM ¹⁰⁴. The Sanchez-Lacombe equation provides a theoretical approach to the parameters required for the addition of SCF into the polymer solution ¹⁰⁵.

Mahmood et al., have added Dimethyl Ether (DME) to PS in their research to investigate its effects on plasticisation ¹⁰⁶. This research was carried out using laboratory scale microcellular processing. The results conclude that with an increase of DME in PS, the solubility of CO₂ into the polymer solution was increased ¹⁰⁶.

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 ^{107, 108}. 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 ¹⁰⁹⁻¹¹². Other nucleating agents that have been shown to enhance the crystallisation of polyolefins are that of GFs ¹⁴, nanoclay ¹¹³ and also 1,3:2,4 bis-O-(4-methylbenzylidene)-D-sorbitol gelling agent (MD) ¹¹⁴. 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 ¹¹⁵.

Poly(lactic acid) (PLA) is a complex polymer to process due to it having low melt strength and slow crystallisation kinetics ¹¹⁶. However, it is seen as more environmentally friendly material as it is a biopolymer and biodegradable ¹¹⁷. 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 ¹¹⁸. 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 ¹¹⁹.

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 ¹²⁰. 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 ⁹⁹. 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 ¹²¹, 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 ¹²². MWCNTs have been introduced to metallocene-catalysed copolymer (PEO), with CO₂ in batch processing; which mitigated the cells rupturing and coalescing by aligning the shear and extensional forces ¹²³.

If nano-cellular parts can be produced through IM and not confined to extrusion or batch processing ¹²⁴⁻¹²⁸, 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 ¹²⁹, or even 200nm ¹³⁰ by using CO₂ in a batch processing setup ^{131, 132}. The next step for this research could be to develop the underpinning manufacturing process to satisfy industrial scale-up ¹³³. 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 ¹²⁸.

Nano-cellular technology could be taken even further if the production of membranes ¹³⁴ could be achieved using nano-cellular injection moulding ^{131, 132}. If this could be replicated through the injection moulding process then cheap, functional nano-cellular membrane manufacture is possible ¹²⁴⁻¹²⁷. Wang et al. have shown that porous parts can be produced using the MIM ¹³⁵; 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 ¹³⁶. This process shows great potential for the future of this technology.

Graphene, a monolayers of carbon atoms which can built into carbon nano-tubes ¹³⁷, is a highly researched material throughout academia and industry ¹³⁸. 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 ¹³⁹. The revival of polymer-based membranes is promising if functional nano-cellular membranes could be produced through MIM processing ¹⁴⁰.

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 ^{141, 142}. 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 ¹. Wang et al have developed a mathematical model of thermal transport through nano-cellular polymers ¹⁴³. 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 ¹⁴³. Furthermore, the thermal conductivity was effectively decreased by increasing the refractive index or the absorption coefficient of the polymer matrix ^{143 144}.

Zhao et al., have produced PP with PTFE fibres foamed parts through high pressure MIM and core-back processing with improved thermal applications ^{145, 146}. 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) ¹⁴⁷.

5.3.2 Acoustic applications

The advances of microcellular technology to be used for acoustic applications has been promising ^{148, 149}. 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 ¹⁴⁸.

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 ¹⁴⁹. 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 ¹⁵⁰.

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 ^{14, 151}. 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) ¹⁵². Stress variations and the presence of micro voids also requires consideration whereby the elastic strain energy has a major impact on the nucleation process ^{153, 154}. Research has demonstrated that approximating the initial cell pressure in the CNT at saturation pressure, leads to major overestimations and therefore inaccurate simulation ¹⁵⁵. 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 ¹⁵⁶.

Pressure rate during the nucleation process is a critical factor to be included in simulation as it facilitates cell formation prediction ¹⁵⁷. 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 ¹⁵⁸. The research showed close alignment to the corresponding empirical experiment work ¹⁵⁸. 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 ¹⁵⁹.

Further modelling could be utilised to inform the prediction of the upper limits of cell density within a microcellular part ^{160, 161}. 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 ¹⁶².

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 ¹⁶³. 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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