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Review

Production of microcellular lightweight components with improved surface finish by technology combination: A review

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ABSTRACT

Microcellular Injection Molding (MIM) is a variant of injection molding technology used to manufacture plastic components, with a cellular structure and reduced weight. However, this technology is characterized for producing components with a poor surface finish and impacted structural integrity. To improve the molded surface appearance, the MIM process conditions have been thoroughly studied, nevertheless, some marks are often noticeable. For this reason, the combination of MIM with decorative technologies enables components with high surface finish, as well as, decorative and functional properties, among other benefits. Since the development of the technology surface improvement has been the focus of many research articles and recently, supported by the progress in machinery, technology integration has emerged as a solution. This review aims to expose the main advantages, disadvantages, and methods for surface improvement of MIM molded components. The key modifications and requirements for the tooling system as the supercritical fluid unit, the fuse, and mold modifications are discussed. The advantages of integration of these different processes with MIM technology are further described and a review of the progress so far is addressed as well as the incorporation of numerical simulation for the MIM components production. For that, technology integration of two-shot injection molding (2 K Shot), In-Mold Decoration (IMD), In-Mold Labeling (IML), and In-Mold Electronics (IME), which represent the biggest integration potential with MIM are examined.

1. Introduction

Injection molding technology is widely used to produce polymeric material components with complex geometry in an automated process, to achieve high throughput rates required for large-scale productions, and for a vast range of products. The variables of the process are diverse and need to be closely monitored to ensure proper component production [1,2]. The rapidly growing demand for lightweight molded components and reduced material consumption have enabled the development of new manufacturing processes. Microcellular Injection Molding (MIM) is a type of injection molding where molded components are produced with a cellular structure, providing a weight reduction, and a shorter cycle time when compared with conventional injection molding (CIM) [3,4]. Despite its many advantages, MIM components are known for their poor surface finish, exhibiting swirl and silver marks on the molded surface. To improve the molded surface appearance, MIM technology has been thoroughly studied by the optimization of the process conditions [5–8], enforcement of the process with the resort of Rapid Heat and Cycle Molding (RHCM) system [5,9], gas counter-pressure [10], core-back [11,12], and co-injection molding, with a formation of a solid shell by CIM and a foamed core [10,13]. However, the complete removal of the marks is not successful. With the emerging of a new and wide range of technologies, such as In-Mold Decoration (IMD), In-Mold Labeling (IML), and In-Mold Electronics (IME), focused on the decoration and functionalization of components surface, the surface finish of MIM molded components ceases to be a problem. The blend of features from each of these technologies may produce better outcomes. In this paper, a

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literature review was employed to summarize the existing studies for the integration of MIM technology with different processes, highlighting the advantages and the potential of the integration of different processes with MIM technology for a high surface appearance.

2. Microcellular Injection Molding

Microcellular Injection Molding (MIM) is a less widespread technology, having recently emerged as an alternative to conventional methods, supported by the lightweight trend, in order to reduce the consumption of raw material needed to produce a finished component [14–16]. With this type of injection molding technology, the molded components are produced with a cellular structure, typically the cells have micro dimensions, 1–100 μm, and a density of 10^7–10^{15} cell/cm^3, providing weight reduction (5%–30%) driven by the hollow core of comprising cells [8,17,18]. The typical cellular structure resulting from MIM technology can be obtained by the introduction of blowing agents in the melted polymer during the injection molding process, creating a one-phase solution during plasticization [19,20], through controlled conditions of pressure and temperature [21]. The introduction of the blowing agent supports the formation of a cellular structure that expands during the filling, packing, and cooling phase, resulting in parts with decreased warpage, making a 1:1 wall-to-rib ratio feasible, increasing the freedom of design [22,23]. With MIM technology, the packing phase can almost be eliminated as the cell expansion process provides a fully packed part with reduced warpage, and decreased residual stress, ensuring dimensional accuracy [9,24]. The resulting molded component is the holder of a high strength-to-weight ratio, high energy absorption, and excellent heat and acoustic insulation [10,25]. MIM requires a faster filling stage, when compared with CIM, to initiate cell nucleation, promoted by the high pressure drop, the moment the melt passes through the gate into the cavity. This, combined with a smaller packing phase leads to a significant reduction in the cycle time, saving up to 15%–40% of the time spent to produce a conventional molded component, depending on the material and designed product [26]. Fig. 1, presents the main differences between the cycle stages of CIM and MIM.

2.1. Blowing agents

The blowing agents used in the process can be either physical (PBA – Physical Blowing Agent), such as Nitrogen (N_2) and Carbon Dioxide (CO_2) [27,28], or chemical (CBA – Chemical Blowing Agent), inorganic or organic components such as Calcium Carbonate ($CaCO_3$) and Talc [29–31]. The PBA variant is a cleaner technology that guarantees a more uniform and denser cell structure with smaller dimensions, for that reason it is usually used in applications where a uniform cell structure is required in order to somewhat maintain the mechanical properties throughout the molded component [4,32]. The addition of a PBA is accomplished by injecting gas in its supercritical fluid (SCF) phase through a dedicated SCF injector. In this phase the gas is in a liquid-like state, obtained by maintaining the PBA above a critical pressure (P_{cr}) and temperature (T_{cr}), allowing the gas to quickly diffuse into the polymer melt, creating a single-phase inside the barrel. After the material passes through the injection system, the pressure drops rapidly, causing high thermodynamic instability, leading to the precipitation of the gas phase out of the polymer, initiating the cell expansion. The high pressure and temperature, characteristic of the injection molding process guarantee that the PBA maintains its SCF phase until the material is injected into the cavity [33]. In Fig. 2 is depicted the foaming process, described above.

The introduction of a cell expansion agent results in injected components with surface defects such as silver streaks and swirls. These defects are caused by the contact of the mixture polymer/gas with the cold mold wall, in the moment of contact, the polymer starts to freeze, and the cells rupture, dragging across the mold wall and resulting in the aspect associated with MIM, as illustrated in Fig. 3.

2.2. Microcellular Injection Molding unit and tool requirements

In MIM, the mold tool and the molding unit need to undergo some modifications, specific to the technology, diverging from CIM in the cost and complexity depending on the blowing agent (CBA or PBA).

2.2.1. Physical blowing agent MIM variant

The physical variant of MIM requires the setup of an injection molding unit with an external PBA storage container. Additionally, a control unit is necessary to timely regulate the amount of PBA introduced in the barrel, under pressure, guaranteeing that the gas is at its SCF phase to properly mix with the polymer melt. In PBA technology, when MuCell® (the most commonly used MIM technology, owned by Trexel Inc.) is employed, a special fuse is required to ensure proper mixing. As depicted in Fig. 2, the fuse is composed of an end region that possesses a characteristic geometry to promote dynamic mixing, assuring the creation of the one phase solution. As such, modifications are made to the end screw section or

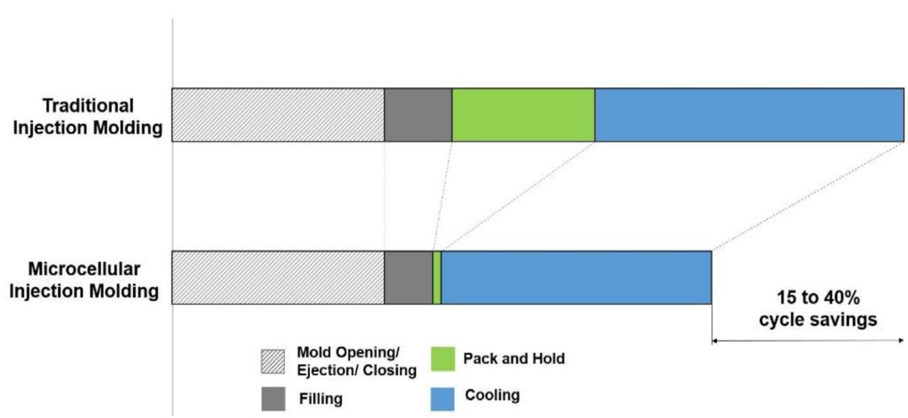

Fig. 1. Comparison between a CIM cycle and a MIM cycle.

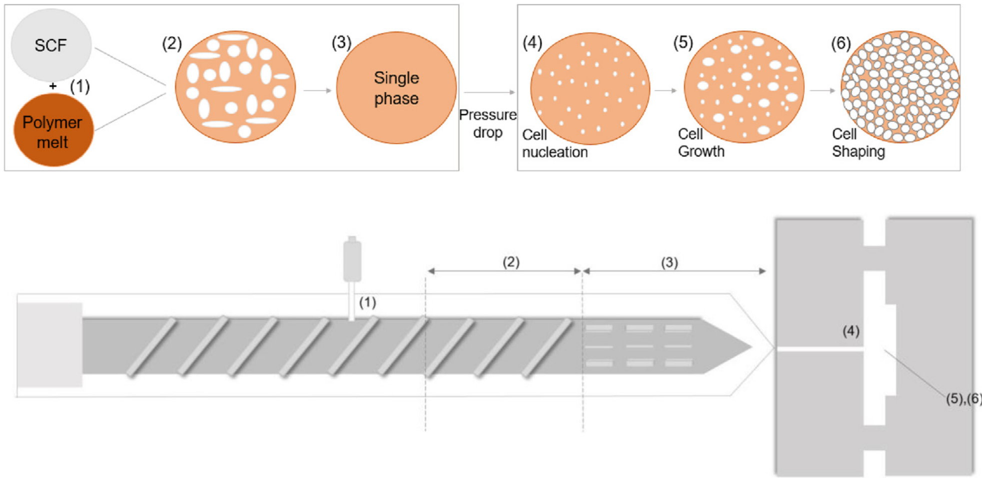

Fig. 2. Physical microcellular foaming mechanism and its stages along the injection molding process.

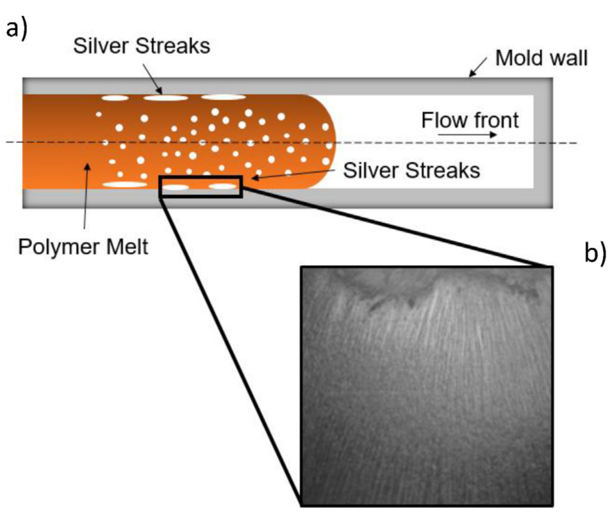

Fig. 3. Flow-induced marks formation scheme (a), molded component representation of silver streaks (b), adapted with the permission of [34].

to the nozzle section by attaching rhombus, Z-mixers, or even static mixers [24]. Due to this increment the MuCell® screw is longer than the commonly used in the conventional injection molding, region 3 of Fig. 2. Recently, Trexel Inc. Introduced a new commercial screw Tip Dosing Module, which increased the performance with lower implementation cost. This solution optimized the mixing module, with reduced space requirements, and is compatible with standard three-zone screws. Alternative processes to MuCell® have emerged, for instance, Yusa et al. [35] developed a MIM technology using non-SCF physical blowing agents through the incorporation of PBA directly from gas cylinders into the molten polymer through an injection valve and vent hole, however, more studies are required before this methodology may be implemented industrially.

2.2.2. Chemical blowing agent MIM variant

The chemical variant of MIM does not require modifications to the injection unit, needing only a shut-off-nozzle [36]. The foaming mechanism is promoted by the reaction of the CBA in the polymer melt, due to the high temperature. Some CBA are exothermic which can potentiate an early blowing of the cells, reducing residence times for the material, consequently, the cell structure is not uniform in most cases [37]. The CBA reactions may also result in byproducts, such as water, which can lead to additional degradation of the polymer matrix [38], and subsequent reduction of mechanical properties, also the subproduct can damage the molding cavity [32,39]. The molding cavity and the screw can also suffer from this reaction and be damaged prematurely, which can influence their durability [32,39,40]. This phenomenon can be avoided by the use of PBA, although, requires more capital investment, however, in the long run, PBA will become advantageous when compared with CBA [40]. In Table 1, is presented a summary comparison of the two MIM variants.

For both variants of MIM, a shut-off-nozzle should be considered to prevent early blowing and the return of the material into the barrel, Fig. 4 [41].

2.2.3. Mold modifications

Concerning the mold modifications, there is a lack of studies that reference the required modifications, and the main referenced alteration is the use core-back technique, which consists of the movement of the mold wall after the cavity is fully filled. The mold movement is applied to promote uniform nucleation and cell growth through the component to be molded. This technique is usually applied to parts that require a higher degree of structural integrity, and cell uniformity is of the most importance [42,43]. The modifications required for the application of core-back require a unique mold design that must be able to retract in a precise way to ensure that the pressure loss caused by the increase of space inside the cavity is equally distributed and consequently boost cell nucleation and growth [11,12]. Although advantageous, this technique requires the additional module that will increase the cost of the overall technology and since many of the developed components with the technology do not require high structural integrity, this technology is often not considered.

2.3. Surface improvement

Although aesthetically poor, MIM may assure the elimination of sink marks, still, it is crucial that the part presents an impeccable surface finish when needed. In order to reduce the effect that the creation of the cellular structure has in the produced part, several parameters of the injection molding process must be closely monitored and optimized, for instance, the filling stage should comprise an injection speed profile with a slow speed in its first stages, and a full speed for the remaining injection time to prevent

Table 1
Comparison of the process and cost: physical and chemical MIM, information gathered from Refs. [32–40].

	Physically MIM	Chemical MIM
Initial Cost (equipment)	High	Low
Cost of blowing agent	Low	Medium
Tool complexity	Low	Medium
Machinery complexity	High	Low
Changes in CIM process	Needs a different injection unit and peripheral equipment	The same injection unit can be used
Durability	High	Medium; Release of byproduct that can damage molding cavity
Cost-benefits	In long term is more beneficial	–

an overgrown structure in the flow front [27]. Due to challenges inherent to the technology, different solutions have been proposed in the attempt to minimize or even eliminate aesthetical defects on the molded part surface. Gas counter-pressure is one of the techniques most used due to its simplicity and capability to achieve good surface results. The technique consists of filling the molding cavity with a gas, increasing the pressure in the flow front, circumscribing the growth of the nucleated cells until the cavity is fully filled. Only then the pressure inside the cavity is reduced and the cells begin to grow, in this stage, the frozen layer is almost fully formed, and the migration of cells to the surface is avoided, resulting in a more uniform surface finish with improved rugosity [44]. Another common MIM variation to diminish surface defects is the mold opening technology, which is applied by completely filling the cavity with polymer melt, ensuring higher melt pressure, and delaying the cell growth while the polymer melt in contact with the mold wall freezes, preventing defects caused by the cells. Then the mold retracts and the cellular growth starts, guaranteeing a smother surface and balanced cell structure [16]. In Fig. 5 a) is presented the surface of a MIM produced part at different distances from the gate. It can be clearly observed surface defects on the molded component, with increasing surface rugosity in the furthest region from the gate, due to the free cell formation in the flow front. In Fig. 4 b) is presented the same part processed with the mold opening MIM technology, with lower rugosity when compared with MIM, as expected.

The RHCM system, also known as Variotherm is also frequently applied to enhance the surface finish, resulting in a molded component with high gloss and with minimized surface defects, such as swirls or silver streaks and weld lines [5]. In this process, the mold and cavity are heated to high temperatures during the filling and packing phase and rapidly cooled during the cooling phase, as presented in Fig. 6.

Dong et al. [45] studied the influence of the RHCM on the surface of the injected MIM parts by using a dynamic mold temperature control system where the temperature was elevated during filling and quickly reduced. In Fig. 6 is presented the result obtained in the study, and as it can be observed there is a significant reduction in surface rugosity was achieved with the increase of mold temperature from 30 °C to 140 °C. Even when the mold temperature is increased to 60 °C, the surface appearance is improved, resulting in parts with a better appearance, as can be seen in Fig. 7.

Additionally, Dong et al. [45] give and plausible explanation to this phenomenon stating that due to the high mold temperatures the cells do not immediately freeze and the continuous flow of the melt removes the surface marks. This process results in the continuous reduction of space inside the molding cavity, increasing pressure and temperature leading to the redissolution of the gas into the melt, granting a smoother surface, as seen in Fig. 8.

When confronting the study developed by Dong et al. [45] with Hou et al. [16] it may be observed that surface finish may be improved either by RHCM or by mold opening technique. However, it is noticeable the lower overall surface rugosity achieved by the RHCM method, which is coherent with what was expected from the technology, since the mold high temperature allows polymer chain mobility, while in the mold opening technique, the material in contact with mold wall forms a frozen layer, constraining the polymer chains mobility, causing the characteristic surface defects of MIM produced component without RHCM.

As already mentioned, core-back technology has also been applied to MIM to promote uniform nucleation by maintaining the mold cavity smaller during the filling phase, as a result, the cell growth is delayed. When the cavity has fully filled the cavity slightly retracts, decreasing the pressure inside the cavity and promoting uniform nucleation and cell growth [42,46]. The technology has also been called High-Pressure Foam Injection Molding

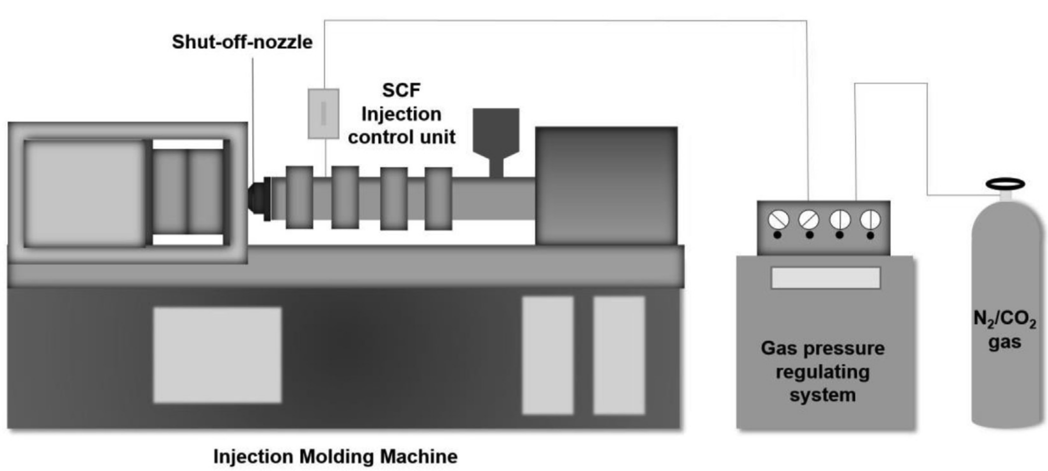

Fig. 4. Physical MIM Injection unit setup example.

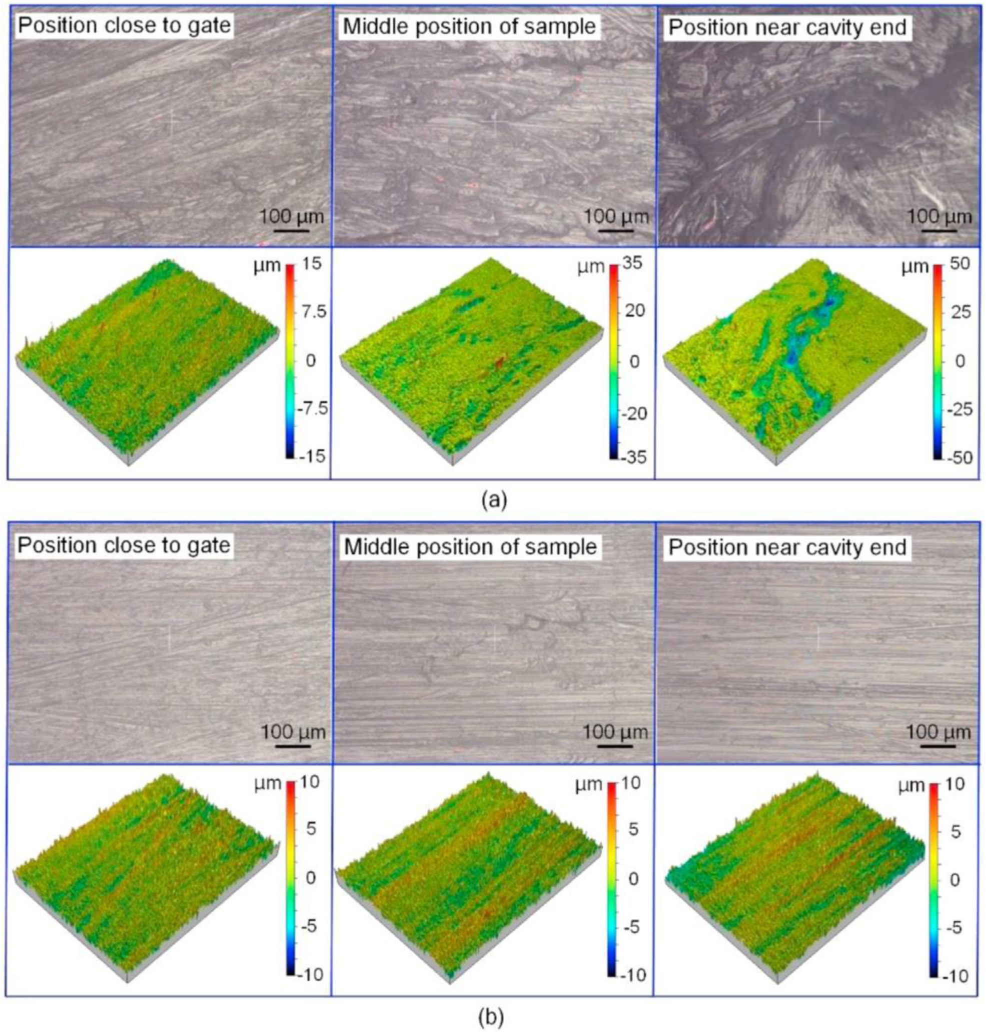

Fig. 5. Surface finish of a MIM molded component a) conventional MIM, b) mold-opening MIM, reprinted with the permission of [16].

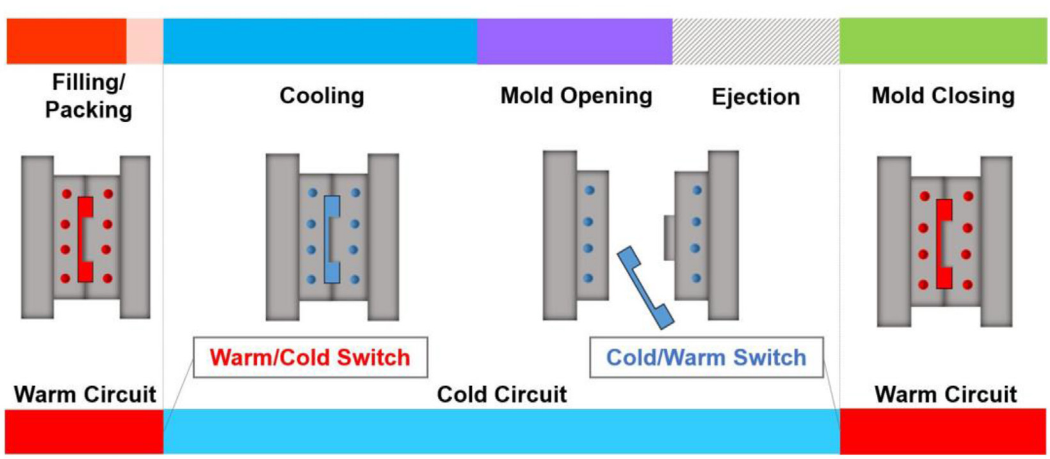

Fig. 6. RCHM cycle representation during MIM.

(HPFIM) [47] since the pressure is maintained inside the cavity during the filling stage. The high pressure and sequential pressure drop can be favorable to a uniform cell structure formation and, usually, is applied for that purpose but, recently, the HPFIM has been applied without the cavity retracting stage, resulting in fully packed parts without a visible cellular structure. The use of this variant resulted in the production of polylactic acid (PLA) glasses fully transparent [48]. The combination of the different

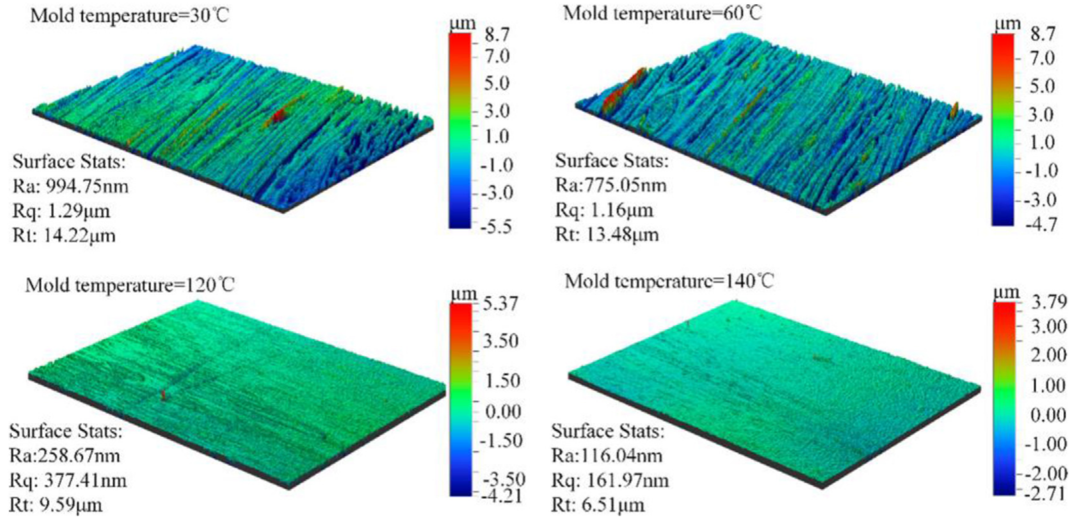

Fig. 7. Surface rugosity analysis for a molded MIM part with different mold temperatures, reprinted with permission from Ref. [45]. Copyright (2018) American Chemical Society.

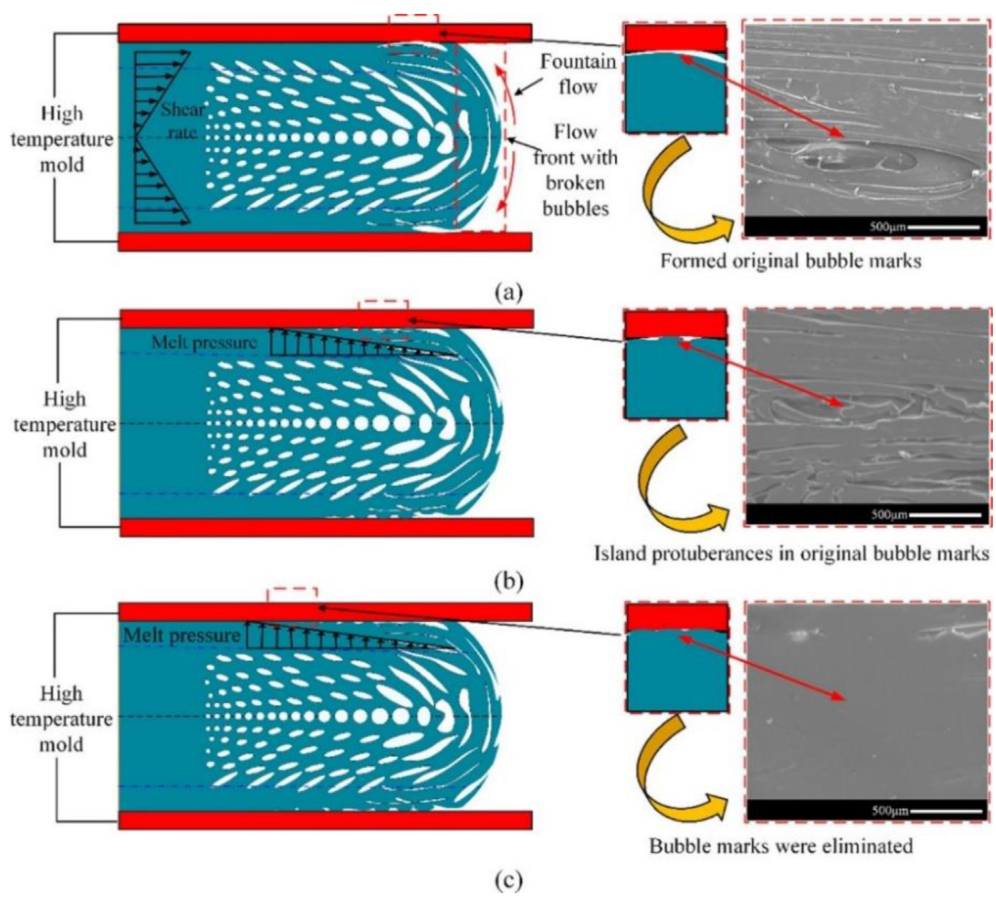

Fig. 8. Proposed explanation for surface cell marks solved with RHCM system: (a) originally generated surface bubble marks, (b) island protuberances, and (c) original surface bubble marks are eliminated. Reprinted with permission from Ref. [45]. Copyright (2018) American Chemical Society.

technologies reviewed above has promoted good results in the molded components produced by MIM. However, even with an improved surface finish, the MIM parts are not aesthetically comparable to conventional injected parts and can be aesthetically unattractive to the consumer. To overcome this problem, the combination of different molding and decorative technologies with MIM will improve the molded component value, with an aesthetically pleasing surface. Therefore, considering the integration of different technologies is a solution to produce high-end products with additional functionality, while reducing the weight of the products and the environmental impact by using less raw material in the process.

2.4. Commercial microcellular injection molding techniques

Similar MIM techniques are commercially available. In most cases, the use of PBA is preferred due to its stability during the injection process when compared to CBA, as a result of CBA exothermic or endothermic properties [24,49]. The most common technologies using PBA are MuCell® [50], OptiFoam [51], and ErgoCell [49]. The application of these technologies demands an additional gas injection unit, which is connected to the plasticizing unit. In addition, as already mentioned, the technologies require the use of an optimized screw to ensure proper gas-polymer mixture [27]. Amongst the presented technologies, MuCell® is by far the most known and used due to its long presence in the market. Trexel Inc., the owner of MuCell® technology, has patented the process in 1984 after being developed in MIT – Massachusetts Institute of Technology. Similar technologies to MuCell® have emerged in the market, such as Ergocell but, eventually, Trexel proclaimed patent rights to the technology, which demanded that when an Ergocell machine was sold it should comprise MuCell® licensing. Later on, the Demag Ergocell retracted their position in the market [27]. As already mentioned IQ Foam® [4], a serious contender to MuCell®, dismisses the need for gas injection into the barrel, injecting the PBA directly in the hopper. Table 2 summarizes the commercial MIM technologies, their present status, and the main advantages/disadvantages.

2.5. Limitations of MIM

Like most technologies, MIM has its limitations, the most commonly linked to the above mentioned, poor superficial finishing [7,13], plus the technology result in parts with a lower mechanical strength of the injected part [27,56], when compared with a CIM part. The surface defects, appear during the filling stage and are generally characterized by swirl marks, caused by the trapped gas on the part surface [57], and silver streaks (flow-induced marks resulting from the shear of microcells when in contact with the cavity wall, freezing immediately) [28,58]. The variation of the mechanical properties is appointed as a consequence of the cellular structure that comprises the molded component with hollow cavities, resulting in the decline of the flexural modulus and tensile strength of the produced part [59]. However, in some cases, this reduction can be negligible as Guo et al. [60] have reported. The team was able to produce injected components with only a small decrease in mechanical property, with a reduction of only 0.9% in tensile strength when compared with the CIM process, having reported the same scale of results for impact resistance and flexural strength tests. Nevertheless, in most cases, it is reported a decrease in mechanical strength that can be detrimental to the molded part [61,62], depending on the final application. For that reason, the cost savings and the material reduction cannot be the key parameters used to select the technology. In fact, the final application of the molded component must be the main factor to determine whether the product may be designed and produced by MIM technology. An example of some technologies that can be employed with MIM are In-Mold Labeling (IML), In-Mold Decoration (IMD), In-Mold Electronics (IME), and over-molding or 2 K shot molding. These technologies will be described below, and their integration with MIM technologies will be address in the following topics.

3. In-Mold Labeling (IML), In-Mold Decoration (IMD), and In-Mold Electronics (IME)

The **IML** and **IMD** technologies, also known as film-insert molding (FIM), are techniques that enable the decoration of a

Table 2
Main MIM techniques and commercial products.

	Commercial Name	Owner	Main Features	Status	Advantages/Disadvantages	Ref.
PBA	MuCell®	Trexel Inc.	Biggest technology in the market Weight reduction up to 30%.	Commercially available	The process depends on temperature and pressure; Needs a specific screw geometry; May require a secondary non-return valve geometry.	[50,52]
	Ergocell	Sumitomo Demag	PBA injected through an additional nozzle located between the plasticization cylinder and injection nozzle.	Requires a MuCell® license to be used	Achieves different degrees of foaming due to an independent piston pump speed, not linked to the screw movement; Requires a great equipment investment.	[40,52,53]
	OptiFoam	Sulzer Chemtech Ltd	The PBA is introduced in the nozzle through a centered torpedo. The injection and mixing unit is fitted between the needle shutoff nozzle and the plasticization unit.	Dropped due to patenting issues	Similar to MuCell®, can achieve homogeneous mixing in the plasticizing phase.	[40,52]
	ProFoam	IKV Aachen	Adds PBA into the mixture to plastic pellets before melting; System installed in the hopper of the injection molding machine.	No longer available	Limited solubility due to the introduction of PBA in the solid state of pellets.	[3,52]
	IQFoam ®	Volkswagen	Contains two gas injector units and a two-chambered unit assembled between the hopper and the barrel where the solid pellets are impregnated with gas; The foaming can be controlled only by the gas pressure, being easily automated.	Commercially available	Reduced cost when compared to similar technologies; Its design reduces losses of gas during injection.	[4]
CBA	TecoCell®	Trexel Inc.	Uses nano-sized $CaCO_3$ particles to produce high density foams with microcellular structure.	Commercially available	Cleaner, more environmentally friendly method when compared to other CBA methods.	[54]
	EcoCell®	Polyfil Corp	Uses nano-sized $CaCO_3$ particles to produce high density foams with microcellular structure.	Commercially available	Similar to TecoCell® but for extrusion purposes.	[55]

molded component during the injection molding process [63,64]. Even though the IML and IMD are often used as synonyms in literature, the main difference between the two is appointed to the end application of the product. For products with shorter lifespans as are packaging for cosmetics and food containers, IML is most used as labels with the goal to enhance the aesthetic appearance of the products, while informing the consumer [64,65]. On the other hand, IMD is used for high-end products, such as toys, appliances, and automotive components [66,67] where better finishing is needed. In some cases, the geometry of the molded component can demand a pre-process where the film is conformed to precisely fit the molded component [68]. The process is carried out by thermoforming of the film, and in these situations, the producer must ensure that the electronic components can meet the formability of the material and resist two different thermal processes. The inserted film may require a pre-processing by thermoforming to ensure proper alignment with the component to be molded, assuring a strong bond between the two parts of the molded component (film + injected part) [69,70].

IME is considered a variant of the film-insert molding, IMD, combined with printed electronics [71], in which the film inserted in the mold is incorporated with electronic components, such as conductive inks [72] surface mount devices (SMDs), or LED's, resulting in a functional high-end product [73,74]. This technique enables a one-step production process by eliminating post-processing necessities [72,75]. However, the fragile constitution of such materials implies a thorough study to determine the proper allocation of the electronic components in the molded part. While being over-molded, the electronic components can degrade or dislocate due to high temperatures and pressure exerted on the film. The working principle of the technologies is very similar, differing in the end application and the components presented on the films. In IML, IMD, and IME, a film is inserted in the mold with precise dimensions, adjusted to the component to be produced, the process starts with the introduction of pre-cut film in an opened mold, by a robotic arm, aligned with the injection molding cycle [69,76], Fig. 9. The fixation of the film in the mold is then accomplished by vacuum, electrostatic fields, or mechanical pins placed in the mold cavity [77]. Most commonly, vacuum or electrostatic fields are used to avoid any damage or visible mark in the molded part as a result of the mechanical pins [76]. IMD and IME products, require durability, hence, the films are thicker and consequently are less suitable for thermoforming, resulting in stretch marks. As a result, the technique is usually associated with shallower and not so complex parts [78].

The technologies presented above, have the advantage of masking any marks present on the surface of the molded component, however, improper preparation of this process may result in defects, such as creases or folds [78], cracked inks [24], and wash-out [79]. Another crucial factor with the techniques lies in the compatibility between the film and the resin to ensure proper bonding between the two different materials [80–82].

4. Two-shot injection molding (2 K)

Two-shot injection molding (2 K shot), is a variant of multi-component molding (MCM) [83]. With this technique it is possible to inject two different materials, or the same material with different colors, resulting in products with great bonding properties [84,85]. As the terminology indicates, this injection process is composed of two sequential steps. In the first step, a molded component is produced inside the mold, and cooled to its solid-state, in the second step, the mold opens, rotates and the second

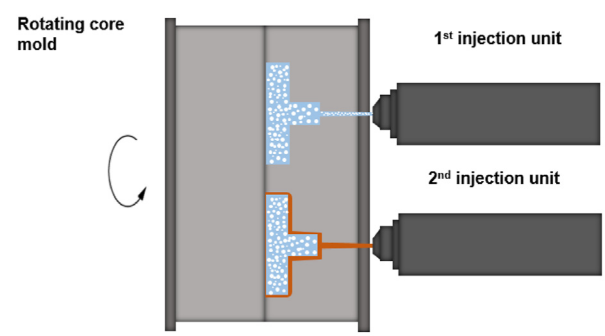

Fig. 10. Two-Component injection molding exemplification.1st with MIM and 2nd by CIM.

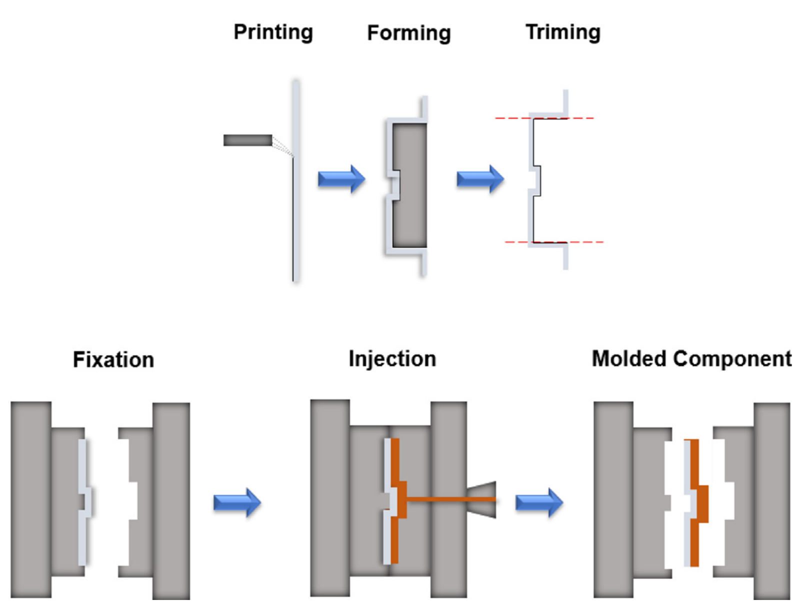

Fig. 9. FIM main steps.

shot of resin is injected into the molding cavity over the first molded component [86]. During the second injection, the interface of the previously injected component is heated, and a bond is formed at the molecular level [87]. Fig. 10 exemplifies the above mentioned process. The bonding of the two parts is assured by a degree of melting of the first injected component during the injection of the second part [88]. This allows the producer to reduce costs in production by cutting to the number of steps necessary to develop a molded part with different combinations [89]. However, the technique is limited by the materials used, where weak bonds can lead to poor mechanical performance [90], for this reason, it is crucial that material compatibility is guaranteed early in the developing steps. As for applications, this technology usually is associated with multi-color or multi-material, and soft-rigid components [91] with the possibility of mastering complex parts with improved efficiency and quality. Its main drawbacks lie in material suitability to the product while maintaining dimensional stability [87]. In Table 3 are presented the key advantages and disadvantages of the techniques discussed above, and referenced the main applications for the different technologies. The techniques are presented independently from each other, with the exception of the FIM production techniques which are presented separated in the end application, as this category represents the major divergences.

As the FIM process, the 2 K shot technology can represent an alternative to cover any surface defects that may exist in the MIM produced component. By injecting a new component over the MIM produced component, all the defects can be completely masked by maintaining the weight reduction provided by MIM in the core of the produced part.

5. Technology integration

The combination of the above mentioned technologies may help reduce the number of steps necessary, in an integrated process, lowering energetic costs and raising efficiency by decreasing production time and increasing cadence [29,40]. The integration of two or more of the mentioned technologies enables the possibility to obtain a product with reduced use of raw material, with higher functionality, and aesthetically agreeable [6,33]. In fact, integrating different technologies is not a new practice in the packaging industry. In 2008, Britton Decorative patented the process of creating raised areas, in packaging, with MuCell® technology combined with IML. Films with 30–50 μm of thickness, the area with resin were injected simultaneously with the expansion agent to ensure that the printed area would not adhere to the plastic material but to the MuCell® part, originating the raised effect [94]. In 2014, Unilever was the pioneer in the production of packaging using Zotefoam's MuCell® Extrusion technology for its Body Wash Bottles combined with IML technology, ensuring a reduction of 15% of the material used in the bottles [95,96]. Some food packaging, such as butter and yogurt are also produced by the integration of MuCell® and IML technology, being reported a 10% increase in thermal insulation, also, achieving 40% clamp tonnage reduction and a 15% decrease in cavity pressure [97,98]. In 2013, Engel presented Dolphin technology [99] as a high-end decorative component for the automotive industry with cost-effective production. The products resulted from a balance between the soft touch and engaging looks. The technology is an outcome of the integration of MuCell®, 2 K injection molding, and compression technology [100]. Chen et al. [57], studied the possibility of reducing visual defects of a MIM molded component with the insertion of a film (PET + PC) in the mold cavity, acting as an insulator between the mold surface and the melt, delaying the heat transfer, combining IMD and MIM technologies. It was reported a significant increase in the surface quality of the molded component and even a decrease in roughness, the setup and results of the introduction of film are presented in Fig. 11, where can be observed a reduction of defects on the surface of the molded part with the increase in thickness.

In an attempt to evaluate the feasibility of a hybrid co-injection and MIM molding process, Turng and Kharbas [84] used different colored materials and co-injected a part, where the core material was produced by MIM and the shell a solid material. It was observed a decrease of the sink marks and an improvement of the dimensional stability of the molded components while maintaining the surface quality presented by the shell material. Similar to Turng's study, skin/core approach Suhartono et al. [101] have also investigated a way to enhance the surface quality of MIM molded components by using co-injection molding, For the production of the parts it was used polypropylene (PP) and PP with glass fiber for MIM production. Higher weight reduction of the injected PP with glass fiber was achieved, explained by higher Melt Flow Index (MFI), and weaker melt strength that allowed better cellular nucleation and enhanced

Table 3
Technologies: advantages, disadvantages, and main applications.

Technologies		Advantages	Disadvantages	Main Applications	Ref.
Film Insert Molding	IMD	Good adhesion; Hides surface part defects; Cleaner technology than similar methods (spray coating); Eliminates the necessity of additional steps, reducing costs; Adds functionality in a one-step process (IME).	Carefully selection of compatible material; compatibility Film introduction induces a differentiated heat transfer that may increase warpage; An incorrect film fixation results in wrinkles and visible defects;	High-end applications with high durability; Displays; Automotive interior parts	[60,67]
	IML			Logo imprinted products Label of food packaging and cosmetics Products for low-end applications	[76,92]
	IME			High-end applications with electronic components Electronic displays Automotive interior parts (central console, instruments panel)	[71,72]
MIM		Reduces part weight - up to 30%; Less raw material used; Cycle time savings - 10%–40%; No packing needed; More design freedom - design of 1:1 (wall thickness to rib structure).	Less mechanical strength Costly investment Requires specific equipment Requires the use of a blowing agent	Automotive part interiors and motor components Packaging, food, and cosmetics HVAC systems	[33,93]
2 K shot		High adhesion and mechanical integrity Higher aesthetics quality can be achieved; Eliminates the assembly step.	Compatibility dependent Requires two injection units and rotational molding plates	Toys Toothbrushes Tool handles	[87,91]

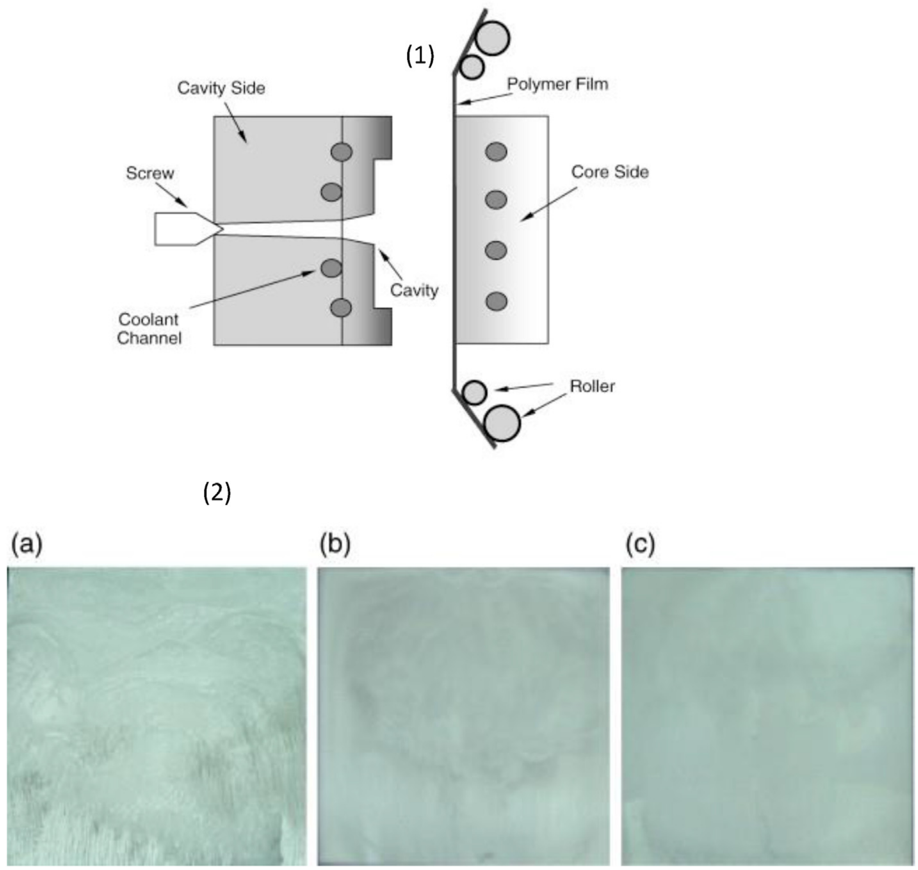

Fig. 11. Illustration of (1) the setup used for the study, (2) results (a) with no film, (b) with a film insert with a thickness of 0.125 mm, and (c) with a film insert with a thickness of 0.188 mm, reprinted with the permission of [57].

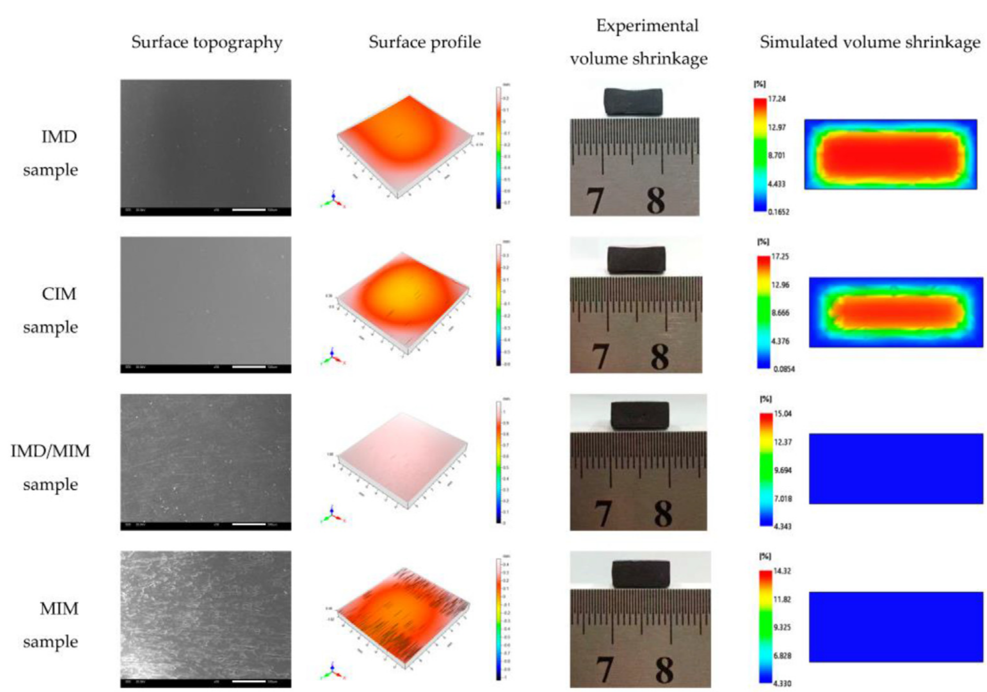

Fig. 12. Surface profile, topography, and shrinkage results from the IMD, CIM, IMD/MIM, and MIM samples tested by Guo's team, reprinted with the permission of [60].

surface appearance when compared to the MIM PP molded component. Recently, Guo et al. [60] presented a thorough study on the integration of IMD/MIM to improve surface finishing. The MIM molded component presented the loss of mechanical properties, with lower stiffness and decreased flexural strength, but showing little difference when compared with the solid counterpart. With the integration of IMD in the process, Guo et al. managed to reduce surface defects, due to the slower heat transfer, results presented in Fig. 12. However, it led to an increase of the warpage in the molded component due to the film in the surface, resulting in contrasting temperatures in the mold and different cooling rates. Also, when comparing MIM with CIM, was reported smaller warpage reduction for the MIM + IMD was due to the expansion of the cells in the cavity. Another significant result refers to higher cell size, on the side which contains the film due to the higher temperature, increasing thermodynamic instability of the gas, lowering the material solubility, which increases the nucleation rate, and the slower cooling phase allows the cell to grow.

The study developed by Guo et al. exhibited an increased warpage when FIM is considered which is in agreement with the literature. However, the preservation of the mechanical property is not coherent, as the produced part possesses regions with different cell sizes, which should be reflected in lower or inconsistent mechanical properties.

In a similar study, Kui et al. [102] have carried out an experiment in an attempt to prove that the application of a film in the mold can be beneficial to reduce the superficial defects of the MIM molded component. In the study, a PET film was used to reduce the surface roughness and nano-$CaCO_3$ was introduced in the composition in order to maintain mechanical properties. The integration of IMD and MIM technologies was carried out with a single film thickness and resulted in different weight reductions, between 2 wt% and 10 wt%. Contrary to the expected, the foamed composites resulted in molded parts with higher tensile properties when compared with the solid molded part produced by CIM. Likewise, for flexural strength, on MIM molded part, when compared with CIM, being the best result achieved with the incorporation of 6 wt% of nano-$CaCO_3$. The cellular structure also improved with the incorporation of the nanoparticles. Above 6 wt% incorporation, the nanoparticles agglomerate resulting in nucleation deficient spots. The film-covered side was evaluated, by surface analysis. A smoother surface with lesser defects was observed as a result of slower cooling. The incorporation of the nanoparticles contributed to the reduction of cell formation on the part surface by restricting their movements from the core to the cavity wall. This study provides interesting insights with the combination of the introduction of nanoparticles in the material composition, and the MIM technology, resulting in products with higher mechanical properties coupled with weight reduction, demonstrating the importance of further investigation in this theme.

In Table 4, are chronologically presented the studies and patents reviewed above, highlighting the technologies employed, materials used, and the main results.

The most recent studies reflect the advantages and benefits of using dedicated software, specifically developed for MIM, in a specialized numerical simulation to prevent problems during production, and predict weight reduction, cell size distribution as well as cell density. By simulating the cell growth, the software possesses the capability to predict warpage behavior and sink marks reduction even to a close approximation of reality. The majority of MIM numerical simulation studies reported in the literature are focused on the process itself [103–105] and few studies focus on the integration of processes, for instance, Yan et al. [102] reported numerical simulation images for temperature prediction, but the numerical simulation study is not further discussed.

In this section, two studies with the integration of technologies and the use of numerical simulation in Moldex3D and Moldflow, the most used software, will be briefly analyzed. The 1st study, already presented above will be further disclosed in this section. As depicted above, the integration and comparison of MIM with different injection molding technologies was analyzed with resort to numerical simulation, with a focus on the shrinkage and warpage behavior of the developed components. The results showed a close approximation to the expected behavior of the molded part, as can be observed in Fig. 13, were the relation of the predicted mold temperatures in all samples (IMD, CIM, IMD/MIM, MIM) with the warpage behavior and the introduction of a film in the cavity influence is examined. Also notorious is the predicted warpage tendency reflected on the molded part. It may also be concluded that the introduction of a film during the molding process will strongly affect the warpage of the MIM and CIM molded components, almost to the same extent, although it was expected lower warpage for MIM.

Yang et al. [106] studied the effect of the incorporation of a film on the surface morphology of a MIM produced component, integrating the MIM and IMD technologies. With resort to numerical simulation was possible to predict the warpage created by the film incorporation and different cooling rates through the molded part. As a form of validation of the numerical study, the part was experimentally reproduced. It was reported a 3% error of simulated temperature compared to the experimental molded component. The effect of the film in the polymer crystallization was also evaluated, concluding that the film incorporation results in a higher crystallization due to slower cooling time, allowing more time for the crystallization process to occur. In the presented cases, the numerical studies helped to predict the warpage behavior of MIM components, as well as the density of the molded part and cell size, however, numerical simulation cannot yet provide an exact replica for the analyzed model, for instance, there is an over prediction of the warpage values in the injected part. For this reason, the use of numerical simulation in the study of integrated processes is not yet widely employed. From what is gathered from the reported studies, the differences between software are scarce and either option, Moldex3D or Moldflow, is valid for simulating the MIM process. It is noteworthy that in the process simulation, as in any Computer Aided Engineering (CAE) software, the results obtained are indicative and enable to predict the material behavior, detect potential problems, and help with cost reduction by digitalizing some product development stages. It is, however, important to underline that this analysis does not replace fundamental knowledge about polymeric materials, mold design, and the injection molding process and, therefore, contains a low percentage of associated error, still, simulations are very useful to support the work of product developers. Therefore, it is possible to notice that new studies using numerical simulation are increasing, and it is expected that in the future, numerical simulations may predict more accurately the injection molding process of MIM components.

6. Microcellular Injection Molding trends and outlooks

MIM technology is nowadays the focus of several projects worldwide. The possibility to produce one material components, and therefore completely recyclable, with reduced material amount is the driving force of the technology as it presents a solution for the hard to recycle fiber filler thermoplastics. In a big production system, it may represent savings of tons of material to produce the parts, translating in savings for the producing companies. In the future, it is expected that the cost of this technology will be lower due to the high demand and the development of new technologies for MIM parts production. The application of such components in

Table 4
Literature review of MIM integration with FIM and Co-Injection technologies.

Title	Year	Technologies employed	Commercial owner	Material	Remarks	Ref.
Development of a Hybrid Solid-Microcellular Co-injection Molding Process	2004	Co-Injection, MIM	–	Polystyrene (PS)	Successful Integration of technologies with shell/core layout, resulting in 90% reduction of sink marks and guaranteeing dimensional stability; Higher weight reduction with the increase of the core volume (microcellular) compared to the core solid part; Formation of a thinner, longer, and more uniform core/shell part.	[84]
Method for producing at least one raised area on a plastic container	2008	MuCell®, IML	Britton Decorative	PP, polyethylene (PET) film	Film thickness of 30–50 μm, combined technology for a raised effect.	[94]
Using thermally insulated polymer film for mold temperature control to improve the surface quality of microcellular injection molded parts	2008	MuCell®, IMD	–	Polycarbonate (PC), PET film, N_2	From no film insert to film thickness variation, maximum 0.188 mm, PBA content of 0.3 wt%; Surface roughness reduced from 5.6 μm to 1.8 μm (78%–93% reduction); MuCell® marks were removed by a film layer of 0.188 mm.	[57]
A new quality of soft touch	2013	MuCell®, IMD	Engel	–	Combines dolphin technology to produce a cost-effective solution with soft touch.	[99]
Unilever launches breakthrough packaging technology that uses 15% less plastic	2014	MuCell®, IML	Unilever®	–	Extruded product, combined with Zotefoams; With the technology, Unilever® reduced the materials used by 15% in the Dove bottles.	[95,96]
MuCell® Technology Beneficial for Unique Packaging Applications: Innovative 3D In-Mold Technology Provides Multi-Sensory Experience for Consumers	2014	MuCell®, IML	Paccor/Unilever	–	The producer claims that achieved, material reduction – 6%; Clamp tonnage reduction - 40%; Cavity pressure reduction – 15%.	[97]
Improvement on the surface quality of microcellular injection molded parts using microcellular co-injection molding with the material combinations of PP and PP-GF	2017	MuCell®, Co-injection molding	–	PP, PP-glass fiber (10 wt%)	Shell/core layout to improve surface quality; 5.1% weight reduction for PP, increased to 8% by glass fiber incorporation; Higher weight reduction on PP/PP without incorporation of glass fiber explained by heavier nucleation, and smaller cells; The co-injected part possesses higher gloss, 46.6% higher when compared with the Mucell® part.	[101]
A combined in-mold decoration and microcellular injection molding method for preparing foamed products with improved surface appearance	2019	MuCell®, IMD	–	PP, PET film	Film thickness of 0.2 mm, PBA content of 0.5 wt%; The numerical simulation used to study shrinkage and warpage tendency; Reduced surface roughness with IMD when compared to MIM; Reduced warpage, 2.1 mm with CIM to 1.6 mm with MIM; Higher warpage than MIM alone due to slower heat transfer and asymmetrical cooling.	[60]
Investigation on Foamed PP/Nano-CaCO3 Composites in a Combined in-Mold Decoration and Microcellular Injection Molding Process	2020	MIM, IMD	–	PP, $CaCO_3$, PET film, N_2	Film thickness of 0.2 mm and PBA content of 0.5 wt% of N_2; Higher tensile, flexural, and impact strength was achieved by the incorporation of 6 wt% $CaCO_3$ when compared with CIM; Film incorporation guaranteed a smoother surface due to higher temperatures and slower cooling times.	[102]
Investigation on forming defects and crystallization of plastic parts in combined in-mold decoration and microcellular injection molding based on a multiphase flow-solid coupled heat transfer model	2020	MuCell®, IMD	–	PP, PET film, N_2	Film thickness variation form 0–0.3 mm, PBA content of 0.5 wt% of N_2; Numerical simulation of IMD/MIM process through implicit domain coupling algorithm (IDCA); Higher warpage for higher film thickness (0.7–1.5 mm); Almost 30% increase in crystallization for 0.2 mm of film thickness.	[106]

stricter industries, i.e. automotive, is still a challenge due to the loss of mechanical properties when compared with CIM. Some studies claim to improve the mechanical properties by controlling the mold and melt temperature [102,107], gas counter pressure [108], or with the introduction of fillers to act as reinforcement [109], nonetheless, it is still insufficient to reach the high standards employed by the automotive industry. New developments have emerged on the production of molded components with a nanocellular structure by controlling high pressure foam injection molding, resulting in molded components with good mechanical strength and reported surface appearance closely relating to the conventional counterpart [110]. However, these findings are still laboratory-based and require further studies to be adopted by the industry.

The poor surface finish of the molded components is its biggest drawback and for that reason, recent studies focus on alternatives to overcome this problem. Chang et al. [111] took advantage of the

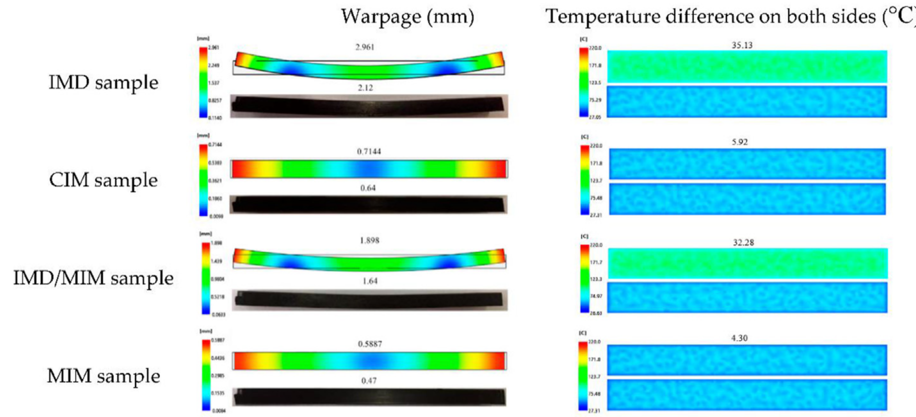

Fig. 13. Comparison of the warpage and temperature difference on both sides among the IMD, CIM, IMD/MIM, and MIM samples, reprinted with the permission of [60].

low packing phase and clamping force needed for MIM and used aluminum material (QC-10) and highly polishable steel (M333), both with high thermal conductivity to produce mold inserts with the cooling system. With this study, it was possible to improve surface finish by a quick cooling rate and without significant damage to the mold inserts. Chen et al. [105] developed a special coating of PFTE and Zirconia to improve MIM produced components surface. These new solutions combined with the already discussed technologies, gas counter-pressure, and RCHM, help to improve the popularity of the technology.

As the industry moves towards sustainable processes, so does the MIM technology, as a new trend by combining MIM with biobased thermoplastics [38,112,113] representing an alternative to the conventional petroleum-based components. However, processing such materials has its challenges, mainly due to the higher processing difficulties associated with these biobased plastics, thus additional research is required. In the specific case of biopolymers, due to the processing difficulties, for example, low processing temperatures are required to improve, the introduction of a PBA in the system reduces de viscosity of the polymer melt, enabling injection molding at lower temperatures than the usual operating temperatures of the polymer [114].

Regarding the integration of MIM with other technologies, it seems to be a clear trend that allows the producer to cut down the materials while giving the product functionality in a one-step process while reducing warpage complications.

7. Concluding remarks

MIM is a clear trend for the injection molding industry, in the present work, the technology is addressed and the integration of 2 K Shot, IMD, IML, IME with MIM is reviewed. The integration, when successful, is of high profit and capable of producing components in a one step process, reducing costs and boosting new developments. It may result in molded components with fewer defects, higher functionality, versatility, and increased product value. However, the process is challenging due to different requirements from the different technologies, increasing in complexity with the conjugation FIM with MIM. This means that the injection molding machine requires a significant capital investment, and the production sequence must be carefully studied early in the developing phase. At an early stage, numerical simulation can help to predict potential problems, address them early and diminish the postproduction modifications. But, as far as we can identify, the combination of these technologies is not easily found in the literature even though it can save time and can be a strong ally as it may result in cost savings. The reduced mechanical performance of the MIM produced components, is still a challenge to overcome, discouraging the industry from appointing MIM as a manufacturing technology to produce a high-end product market. This is why, the integrative setup should be considered as an alternative, where mechanical performance may be enhanced and the aesthetic element optimized while retaining the weight loss characteristic of the MIM molded part. Since this type of process integration is still underexplored, new problems are arising, for instance, when FIM is combined with MIM, the residual gas that slowly migrates to the surface of the molded part is trapped in the film/plastic interface. As a solution, process optimization with variation of gas introduction (wt%) and injection velocity could be considered to prevent such issues. Also, the incorporation of nanoparticles should be considered to overcome the loss of mechanical properties. These are some examples where the industry should focus its innovative efforts. Thanks to the current demand in the European Union for the reduction of material waste and plastic, in recent years more studies have been published on MIM integration with other technologies. In the future, it is expected that the integration of these technologies will be a strong part of the injection molding market, especially for high-end applications.

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Conflicts of interest

The authors declare that there is no conflicts of interest.

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