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A Comprehensive Review of Emerging Trends in Advanced Injection Moulding Technologies

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Abstract

Injection molding is a widely used manufacturing process in the plastics industry, enabling the efficient and cost-effective production of complex components.This paper presents a comprehensive review of major thermoplastic materials used in injection moulding, including polypropylene (PP), polyethylene (PE), polystyrene (PS), acrylonitrile-butadiene-styrene (ABS), polyvinyl chloride (PVC), polymethyl methacrylate (PMMA), and polyamide (PA). It also examines nine advanced moulding technologies, namely water-assisted injection moulding (WAIM), gas-assisted injection moulding (GAIM), microcellular injection moulding (MIM), variable mold temperature technologies (VMTT), microinjection moulding, rapid thermal cycling moulding (RTCM), multicomponent injection moulding, metal injection moulding, and reaction injection moulding (RIM). The effects of key process parameters on product quality, mechanical properties, and dimensional accuracy are reviewed. Environmental concerns, including energy consumption, greenhouse gas emissions, and waste generation, are discussed along with sustainable manufacturing strategies. The paper further highlights emerging trends such as automation, digitalization, biodegradable materials, and intelligent quality control systems that are expected to drive future developments in injection moulding technology.

Keywords: *Injection moulding; thermoplastics; process parameters; gas-assisted moulding; microcellular moulding.*

1. Introduction

Among the various manufacturing technologies developed over the past century, injection moulding occupies a uniquely prominent position. Its capacity to produce complex plastic parts in high volumes with consistent dimensional accuracy has made it indispensable to modern industry. From automobile dashboards and medical syringes to electronic housings and children's toys, injection-moulded components permeate virtually every facet of contemporary life. The process, in essence, involves melting a thermoplastic material, forcing it under high pressure into a precisely shaped mold cavity, allowing it to cool and solidify, and then ejecting the finished part, a cycle that can repeat thousands of times with minimal variation [1,2].

The historical roots of injection moulding can be traced to the nineteenth century, when early machines were developed to press natural materials like shellac and cellulose nitrate into buttons and combs. The technology remained relatively primitive until the twentieth century, when advances in polymer chemistry introduced synthetic plastics such as polyethylene, polypropylene, and polystyrene that proved far more amenable to moulding [3]. A pivotal moment came in 1946 with the introduction of the first practical screw-based injection moulding machine, which revolutionized the industry by enabling automated, continuous processing. In the following decades, the emphasis shifted toward greater machine power, tighter process control, and expanding the range of processable materials. By the late twentieth century, injection moulding had become the single most widely used plastic fabrication technique worldwide [4].

What distinguishes contemporary injection moulding from its earlier incarnations is the sheer sophistication of both the machinery and the process variants now available. Modern injection moulding systems incorporate

computer-controlled hydraulic and electric drives, real-time cavity pressure sensors, conformal cooling channels fabricated through additive manufacturing, and adaptive control algorithms that adjust parameters on the fly [5,6]. Alongside conventional moulding, a diverse family of specialized techniques has emerged — each designed to address specific challenges or unlock particular product properties that standard moulding cannot achieve [7]. Gas-assisted and water-assisted moulding enable the creation of hollow sections within solid parts, dramatically reducing weight and material consumption [8]. Microcellular moulding introduces a controlled foam structure that simultaneously lowers density and enhances impact resistance. Rapid thermal cycling allows the mold surface to be heated above the glass transition temperature of the polymer before injection and cooled rapidly thereafter, yielding parts with mirror-smooth surfaces and eliminated weld lines [9,10].

This review synthesizes recent research on both the materials and the techniques that define the current state of injection moulding technology. The first major section examines the thermoplastic polymers most commonly processed by injection moulding, drawing on experimental and computational studies to characterize how each material responds to key process variables. The second section provides a detailed survey of advanced moulding techniques, discussing the operating principles, distinctive advantages, inherent limitations, and documented research findings for each. The third section addresses the applications and future scope. The paper concludes with a synthesis of current trends and an outlook on the directions in which the field is likely to develop.

2. Review of Literature

Farotti et al. [11] conducted one of the significant studies on the injection moulding of polypropylene (PP), focusing on the relationship between processing parameters and mechanical properties. The authors investigated the effects of melt temperature, mold temperature, injection pressure, and cooling time on the performance of commercial polypropylene. Their findings revealed that mold temperature and injection pressure strongly influenced the mechanical behavior of the moulded products, while excessive parameter values could result in product distortion. Andrzejewski et al. [12] conducted a comparative investigation on the use of natural fillers in polypropylene injection moulding. The researchers evaluated buckwheat hulls as an alternative to conventional wood fibers and reported that buckwheat hulls could be successfully incorporated into polypropylene composites, offering a sustainable and effective reinforcement option. Wang et al. [13] carried out research on the injection moulding of polypropylene single-polymer composites (SPCs). The study examined the influence of cylinder temperature, injection pressure, holding time, and other processing conditions on the weight and tensile properties of moulded specimens. The results demonstrated that these processing parameters significantly affected the final mechanical performance of the composites. Kosciuszko et al. [14] investigated remoulding shrinkage and void formation in polypropylene mouldings produced by injection moulding. The authors reported that the use of cellular injection moulding combined with an extended holding phase reduced gas pore formation and minimized surface defects, leading to improved product quality. Leyva-Porras et al. [15] conducted a study to evaluate the effects of injection moulding conditions on the microstructure and crystallinity of low-density polyethylene (LDPE). Their results indicated that mold temperature had a significant influence on crystallinity, while the interaction between mold temperature and melt temperature affected the size of polymer spherulites. Khan et al. [16] performed parameter optimization studies on recycled high-density polyethylene (HDPE) products manufactured by injection moulding. Using Grey relational analysis, they determined the optimal combination of processing parameters required to improve product quality and dimensional consistency. Sadabadi et al. [17] investigated fiber orientation behavior in short-glass-fiber-reinforced polystyrene composites produced by injection moulding. Their analysis showed that injection flow rate had a greater influence on fiber orientation than mold wall temperature, emphasizing the importance of flow conditions during processing. Rahimi et al. [18] examined the effects of repeated reprocessing cycles on the mechanical properties of ABS materials. The study demonstrated that multiple injection moulding cycles altered the material characteristics, highlighting the need for careful control during recycling and reprocessing

operations. Llado et al. [19] conducted research on PVC injection-moulded fittings and analyzed the factors responsible for surface efflorescence defects. The authors concluded that injection rate was the primary factor influencing defect formation, while melt temperature was identified as the second most important parameter. Liu et al. [20] conducted research on lightweight basalt-fiber-reinforced composite foams fabricated using microcellular injection moulding. The results demonstrated enhanced cell density, reduced cell size, and improved mechanical performance, confirming the suitability of the process for lightweight structural applications. Chen et al. [21] proposed an electromagnetic induction heating system integrated with water cooling for variable mold temperature technology. Their findings indicated that the developed approach significantly improved surface quality and reduced surface roughness in moulded components.

3. Materials Used in Injection Moulding

The selection of an appropriate polymer is among the most consequential decisions in injection moulding product development. Different plastics exhibit widely varying melt viscosities, thermal properties, shrinkage behaviors, and mechanical characteristics, all of which profoundly influence both the processing conditions required and the properties of the finished part. The following subsections examine seven of the most extensively used thermoplastics in injection moulding, highlighting both their material characteristics and the findings of recent process-focused research.

3.1 Polypropylene (PP)

Polypropylene belongs to the polyolefin family and consistently ranks among the highest-volume polymers processed by injection moulding globally. Its popularity rests on a favorable combination of properties: low melt viscosity for easy flow into complex mold geometries, good resistance to chemical attack and mechanical abrasion, relatively low density, and competitive cost. In the molten state, PP exhibits the kind of smooth, fluid behavior that allows it to fill thin-walled sections and intricate features that would challenge more viscous materials. The broad range of PP grades including homopolymers, random copolymers, and impact copolymers, along with the availability of reinforced and filled compounds, makes it adaptable to an exceptionally wide range of end-use requirements. Commercial applications encompass packaging containers, automotive bumper fascias and interior trim, medical devices and syringes, technical textiles, electrical component housings, bathroom fittings, and a host of consumer goods.

The influence of process parameters on PP moulding has been the subject of substantial research. Farotti and colleagues conducted a systematic investigation of the correlations between injection moulding inputs, specifically melt temperature, mold temperature, injection pressure, and cooling time and the resulting mechanical properties of commercial PP specimens. In a complementary line of inquiry, [12] Andrzejewski and associates examined the potential of buckwheat hulls as a renewable filler for PP compounds processed by injection moulding, comparing their performance against the more conventional wood fiber. The study validated the feasibility of buckwheat hull-filled composites as a sustainable alternative, with acceptable mechanical properties relative to the wood fiber benchmark.

Research by [13] Wang and colleagues into single-polymer composites (SPCs) of PP in which a fabric insert made from PP fibers is encapsulated within a PP matrix during injection revealed that cylinder temperature, injection pressure, and holding time each exerted significant effects on both sample weight and tensile properties, though in different and sometimes counterintuitive ways. [14] Kosciuszko and co-workers subsequently contributed an important analysis of post-moulding shrinkage in PP, demonstrating that the combination of a cellular injection strategy with an extended holding phase effectively reduces gas porosity and the associated surface voids that compromise dimensional accuracy.

3.2 Polyethylene (PE)

Polyethylene represents perhaps the most structurally diverse of the commodity thermoplastics, existing in several distinct morphological forms that differ substantially in their processing and performance characteristics. Low-density polyethylene (LDPE) is produced by high-pressure radical polymerization and features a highly branched molecular architecture that imparts flexibility, transparency, and low melting point. High-density polyethylene (HDPE), synthesized at lower pressures using coordination catalysts, has a predominantly linear chain structure that confers higher crystallinity, stiffness, and tensile strength. Linear low-density polyethylene (LLDPE) bridges the two, offering improved tear resistance and puncture resistance relative to LDPE. All three variants are regularly processed by injection moulding, with the choice among them dictated by the mechanical and optical demands of the intended application.

PE injection moulding research has addressed a range of practically important questions. [15] Leyva-Porras and associates studied the microstructure and crystallinity of LDPE samples moulded at different combinations of cylinder and mold temperatures, finding that the interaction between these two temperature variables exerts the greatest influence on spherulite size, while mold temperature specifically governs the degree of crystallinity

For recycled HDPE,[16] Khan and colleagues employed Grey relational analysis to identify the optimal combination of injection moulding parameters, arriving at a melt temperature of 240°C, clamping pressure of 255 N/m², injection time of 0.6 seconds, and holding time of 30 seconds as the settings most conducive to dimensional and mechanical quality. This work is particularly relevant given the growing imperative to incorporate recycled content in plastic products. [22] Djurner and co-workers, investigating the effect of injection pressure across low and high molecular weight PE grades, established that elevated pressures during HDPE processing produce materials with more desirable mechanical properties, a finding with direct implications for the design of injection programs for structural parts.

3.3 Polystyrene (PS)

Polystyrene is a versatile thermoplastic obtained by the polymerization of styrene monomer, characterized in its natural state by high transparency, elevated surface gloss, and relatively low melting point. These attributes make it both aesthetically attractive for visible consumer applications and processing-friendly from a cycle time standpoint. PS is classified as an amorphous thermoplastic, meaning it lacks the long-range crystalline order found in polymers like PE and PP, and consequently exhibits different flow and solidification behavior during injection. Its applications span acid-resistant piping, electrical insulators and housings, food packaging, toys, haberdashery items, and in its expanded form (EPS), the ubiquitous thermal insulation panels used in construction and refrigeration.

Several research themes have attracted attention in the context of PS injection moulding. Studies on mold surface coatings have demonstrated that appropriate surface treatments can significantly reduce melt flow resistance through the injection system, allowing for faster filling at lower pressures with attendant benefits for cycle time and energy consumption. A particularly instructive comparative study pitted amorphous PS against semi-crystalline PP under matched injection moulding conditions; it was found that the crystalline character of PP suppresses foam formation, while amorphous PS exhibited the highest expansion coefficient at elevated injection speeds combined with low mold temperatures — a difference attributable to the fundamentally different solidification mechanisms of the two polymer classes.

Work by [17] Sadabdai and Ghasemi on short glass fiber-reinforced PS (SGF-PS) composites used numerical simulation to evaluate the fiber orientation tensor in injection-moulded rectangular plates, revealing that injection flow rate exerted a larger influence on fiber orientation than mold wall temperature did. Because fiber orientation directly governs the anisotropic mechanical properties of short fiber composites, this finding has significant practical implications for the structural design of reinforced PS mouldings.

3.4 Acrylonitrile-Butadiene-Styrene (ABS)

ABS is a three-component terpolymer whose name reflects its constituent monomers: acrylonitrile, butadiene, and styrene. Each component contributes distinct properties to the blend, the acrylonitrile confers chemical resistance and thermal stability, the butadiene rubber phase provides toughness and impact resistance, and the styrene imparts rigidity, surface gloss, and processability. In standard commercial grades, the composition spans approximately 15–35% acrylonitrile, 5–30% butadiene, and 40–60% styrene, with the exact ratios tuned to balance the competing demands of particular applications. ABS is classified as an amorphous polymer, which means it has no distinct melting point and softens progressively upon heating, a characteristic that simplifies processing window management but also makes it sensitive to moisture-induced surface defects if not dried adequately before moulding.

The injection moulding of ABS has been extensively studied from multiple perspectives. Using the Taguchi method combined with analysis of variance (ANOVA), researchers established quantitative linear models relating injection parameters to mechanical properties including elastic modulus, tensile strength, flexural modulus, and charpy impact strength, providing a practical basis for parameter optimization in industrial settings. Energy consumption in ABS injection moulding was analyzed through direct measurement of equipment power draw synchronized with moulding quality assessment; the study identified holding time and mold cooling time as the parameters with the greatest influence on total energy use per cycle, pointing to these stages as the primary targets for energy efficiency improvement. Additional research assessed the shrinkage of ABS automotive components as a function of injection pressure and cooling system design, while comparative work by [23] Lay and associates quantified the differences in physical and mechanical properties between ABS parts produced by conventional injection moulding versus fused deposition modeling (FDM), demonstrating significant advantages for the injection-moulded route in most mechanical categories.

3.5 Polyvinyl Chloride (PVC)

Polyvinyl chloride occupies a distinctive niche among commodity thermoplastics by virtue of its inherent flame retardancy, chemical resistance, and the extraordinary range of properties achievable through compounding. In its rigid form, PVC is hard and dimensionally stable, making it the material of choice for pipes, window profiles, and structural sheet applications. In its plasticized form, it is soft and flexible, serving as the basis for flooring, cables, medical tubing, and countless flexible consumer products. In the construction sector, PVC piping systems handle drinking water, sewage, and industrial process fluids, where its corrosion resistance and long service life make it particularly valued. The furniture, medical, and automotive industries also rely on PVC in a variety of injection-moulded components.

Injection moulding of PVC presents certain processing challenges not encountered with polyolefins, most notably the material's sensitivity to thermal degradation, which requires careful management of melt temperature and residence time to avoid hydrogen chloride release. Research by [19] Llado and Sanchez investigated the formation of surface blush (efflorescence) on injection-moulded PVC fittings, identifying incorrectly set injection rate as the primary cause, with melt temperature as a secondary contributing factor. [24] Ahmed and colleagues approached the warpage problem in PVC mouldings from a machine learning perspective, developing a mathematical model capable of predicting warpage as a function of process inputs, thereby enabling pre-production optimization to minimize scrap.

3.6 Polymethyl Methacrylate (PMMA)

Polymethyl methacrylate, commonly sold under trade names such as Plexiglas and Perspex, is prized above all for its exceptional optical clarity, which approaches that of optical glass, combined with significantly lower density and superior resistance to ultraviolet degradation. These properties make PMMA indispensable in lighting fixtures, display windows, optical lenses, and electronic device covers. In the dental and orthodontic fields, PMMA serves as the primary material for prosthetic denture bases and orthodontic appliances, where its biocompatibility, ease of repair, and ability to be tinted are valued. The injection moulding of PMMA is technically demanding because residual stresses, arising from the combined effects of thermal gradients, flow-induced molecular orientation, and cooling shrinkage can impair both optical quality and mechanical performance.

Research by [10] Zhang and co-workers employed injection moulding simulation to systematically map the effect of processing parameters on residual stresses in PMMA micro-pillar arrays, identifying the parameter combinations that minimize both the magnitude and the spatial non-uniformity of residual stresses. [25] Weng and colleagues used molecular dynamics simulation to investigate the formation mechanism of residual stresses at the nanoscale level in micro-injection moulded PMMA, providing mechanistic insights that complement macroscale experimental observations. It has also been reported that injection-moulded PMMA can exhibit lower impact and bending strength than thermally cured material, an important consideration in structural applications, though these limitations can be substantially mitigated through the incorporation of appropriate nano-tube or particulate additives.

3.7 Polyamide (PA)

Polyamide, universally recognized under the trade name Nylon in its various grades, is a semi-crystalline engineering thermoplastic with an impressive combination of mechanical strength, stiffness, fatigue resistance, and thermal stability. The presence of amide linkages in the polymer backbone enables strong interchain hydrogen bonding, which is primarily responsible for the elevated melting points and mechanical performance that distinguish polyamides from commodity plastics. PA6 and PA6.6 are the most widely processed grades by injection moulding, finding extensive application in automotive under-hood components, electrical connectors, structural brackets, gears, and bearings, wherever a combination of mechanical performance and temperature resistance is required.

The injection moulding behavior of polyamide has attracted research across several dimensions. The mechanical properties of PA6.6 composites reinforced with long glass fibers were investigated as a function of moulding conditions, with findings demonstrating that fiber length retention during processing is a critical variable governing composite stiffness and strength. The feasibility of processing PA6 with natural Curauá cellulose fibers was assessed, expanding the range of sustainable reinforcement options available for polyamide composites. Microcellular injection moulding of PA6 nano composites incorporating nano clay was also explored, yielding materials with modified microstructure and mechanical property profiles relative to their non-foamed counterparts. Combined studies involving PA, PP, and nano clay established that compatibilizer chemistry plays a decisive role in determining the morphology and mechanical performance of these ternary nanocomposite systems.

4. Advanced Injection Moulding Techniques

The limitations of conventional injection moulding, including residual stresses, surface defects, uniform solid wall construction, and constraints on part geometry have driven the development of a rich array of specialized variants. Each technique modifies one or more aspects of the conventional process to achieve specific improvements in product properties, process efficiency, or design freedom. The following subsections examine nine such techniques in depth.

4.1 Water-Assisted Injection Moulding (WAIM)

Water-assisted injection moulding represents one of the more distinctive departures from conventional practice, employing pressurized water as the medium to create hollow channels within injection-moulded parts. The technique belongs to a broader category of fluid-assisted processes termed Fluid Projectile-Assisted Injection Moulding (F-PAIM), which also encompasses gas-assisted moulding, and can be implemented via either a short-shot method or an overflow method. In the overflow configuration, the more common approach, the mold cavity is first completely filled with molten polymer, after which a bullet-shaped projectile positioned on the fluid nozzle is driven through the polymer core by pressurized water, displacing the still-molten interior material into a secondary overflow cavity. The water pressure is maintained during cooling to compensate for shrinkage and preserve the hollow geometry, and then drained before the mold opens.

The water injection unit in a WAIM system comprises a high-pressure pump, a temperature-controlled water reservoir, a pressure accumulator, and an automated control circuit governing injection timing and pressure. These components are typically mounted on a self-contained mobile unit that can be interfaced with a conventional injection moulding machine without major modification. Research has explored different water pin designs, including stationary pins and movable configurations, as well as ring-type and orifice-type pins, finding that pin geometry determines both the shape of the hollow core and the uniformity of residual wall thickness.

One of the notable challenges associated with WAIM is the phenomenon of water fingering, in which water channels escape outside their intended path in the polymer melt, producing irregular hollow geometries and internal surface defects. Research by [12] Ahmadzai and Vesh on WAIM of semi-crystalline PP identified high mold temperature and extended holding time as the conditions most conducive to achieving low shrinkage and uniform wall thickness, the two most practically important quality indicators for hollow tubular mouldings.

4.2 Gas-Assisted Injection Moulding (GAIM)

Gas-assisted injection moulding achieves a conceptually similar result to WAIM, the creation of hollow sections within an otherwise solid moulding, but uses an inert gas (typically nitrogen) rather than water as the pressurizing medium. The gas is injected into the partially filled or fully filled mold cavity after the initial plastic charge has been introduced, penetrating the still-molten core to displace material and create an internal gas channel. The gas pressure is maintained throughout the cooling phase, ensuring intimate contact between the polymer and the mold wall and compensating for volumetric shrinkage. This controlled packing mechanism significantly reduces residual stress, warpage, and sink marks relative to conventionally moulded parts, while simultaneously reducing the amount of polymer required.

The practical advantages of GAIM extend well beyond simple material savings. By reducing the clamping force required to hold the mold closed against injection pressure, since the core of the part is filled with low-pressure gas rather than polymer, GAIM allows larger parts to be produced on smaller machines, with direct cost implications. Research into GAIM of a plastic compact disc holder confirmed that simulation-optimized process parameters produced substantial reductions in both production time and unit cost. The ability to reduce or eliminate scorch marks by lowering clamping pressure is a further benefit documented in the literature, particularly relevant for parts with deep ribs or bosses where gas trapping is otherwise problematic.

The use of gas-assisted processing has been successfully extended to eco-composites based on rice husk-filled polypropylene, demonstrating that GAIM can overcome the elevated shear viscosity that limits conventional injection moulding of natural fiber composites. The integration of GAIM with microcellular injection moulding has also been demonstrated, with the combined process yielding parts with simultaneously reduced weight, improved surface finish, and enhanced mechanical properties, benefits that neither technique achieves as effectively in isolation. The Phan-Thien Tanner (PTT) viscoelastic constitutive model has been applied to GAIM simulation, enabling more realistic representation of the complex polymer melt rheology encountered during gas penetration.

4.3 Microcellular Injection Moulding (MIM)

Microcellular injection moulding, commercialized under the trade name MuCell®, represents a fundamentally different approach to lightweight part production. Rather than creating discrete hollow channels, MIM distributes a vast number of very small closed gas bubbles uniformly throughout the polymer matrix, producing a cellular structure with dramatically reduced density but substantially improved impact resistance relative to the equivalent solid material. The process achieves a material reduction of 30 to 40% compared with conventional moulding while simultaneously eliminating the shrinkage, warpage, and sink marks that plague solid parts, because the expanding gas compensates for cooling shrinkage.

In the MIM process, an inert gas, typically nitrogen or carbon dioxide is dissolved in the polymer melt under supercritical conditions within the barrel of the injection unit. When the pressurized melt is injected into the mold cavity and the pressure drops, the gas comes out of solution to nucleate millions of uniformly distributed microcells, typically 10 to 100 micrometers in diameter. The nucleation kinetics and cell growth dynamics can be controlled through careful manipulation of process parameters, enabling the engineer to dial in a target cell size and density for specific structural and acoustic requirements.

Research by [26] Hou and colleagues demonstrated that incorporating talc at 10 weight percent as a nucleating agent in PP foams produced an average cell size of 56.5 micrometers and a cell density of 1.54×10^{3} cells/cm^3 at a weight reduction of 62.1% the degree of microstructural control achievable through additive strategies. The MIM technique has been applied to polyether-ether-ketone (PEEK), a high-performance engineering polymer used in aerospace applications, yielding microcellular parts with a weight reduction factor of 17.29% and a tensile strength of 74.13 MPa after process optimization. The combination of MIM with in-situ fibrillation of polytetrafluoroethylene (PTFE) has produced exceptionally lightweight foams based on polylactic acid (PLA) with enhanced mechanical and thermal insulation performance, a development of particular relevance to sustainable packaging and biomedical applications.

4.4 Variable Mold Temperature Technologies (VMTT)

The temperature distribution within the mold cavity during injection moulding exerts a pervasive influence on virtually every aspect of part quality, from surface finish and weld line strength to crystalline morphology and residual stress levels. Conventional cooling systems, relying on straight or simply curved water channels machined into the mold plates, often struggle to provide sufficiently uniform and responsive temperature control, particularly in molds with complex geometries or demanding quality requirements. Variable mold temperature technologies address this limitation by enabling dynamic manipulation of the mold surface temperature throughout the moulding cycle.

Several heating strategies have been developed and investigated. High-pressure hot water heating can achieve mold surface temperatures up to approximately 180–200°C, but requires robust piping connections capable of handling the pressurized water flow. Hot oil heating extends the temperature range to approximately 300°C, though the low heat transfer coefficient of oil penalizes energy efficiency. Steam heating achieves particularly rapid temperature ramping, raising the mold surface from 35°C to 135°C in as little as 11 seconds, making it attractive for rapid thermal cycle applications. Electric resistance heating, using heating plates or tubes, offers precise local control and eliminates the need for a fluid circulation infrastructure. Electromagnetic induction

heating combined with water cooling, as proposed by [21] Chen and colleagues was shown to improve surface roughness by 80%, with simultaneous reduction of surface irregularities.

[27] Seo identified conformal cooling channels, produced by additive manufacturing (3D printing) to follow the contours of complex mold geometries far more closely than conventionally drilled channels, have been shown to reduce cooling time by up to 30% compared with conventional channel layouts. Statistical analyses of variable mold temperature parameters by [29] Chauhan and associates identified melt temperature as the most influential parameter among compression time, mold temperature, melt temperature, and pressure, a finding consistent with the fundamental role of polymer rheology in determining part quality.

4.5 Microinjection Moulding

The inexorable trend toward miniaturization in electronics, medical devices, and optical systems has created a need for injection-moulded components with feature dimensions in the sub-millimeter range and part masses sometimes below a tenth of a gram. Conventional injection moulding equipment and practice are poorly suited to this scale: the rheological behavior of polymer melts in very thin sections differs fundamentally from that in conventional parts, thermal effects are amplified, and the tolerances required for micro-scale features exceed the capabilities of standard moulding systems. Microinjection moulding (μIM) has emerged as the specialized technology to meet these demands, with research and industrial development advancing rapidly over the past two decades.

The characteristic challenges of microinjection moulding include the formation of a frozen polymer layer at the mold wall, which in a micro-scale cavity can represent a substantial fraction of the total cross-section and the difficulty of maintaining uniform temperature distribution across very small cavity areas. [28] Wolff and colleagues addressed the frozen layer problem through the development of an internal gas-assisted mold temperature control system combined with pulsed cooling, demonstrating that this approach could increase mold filling from 65.4% to 100% by applying localized heating within the cavity region. An innovative approach to the temperature uniformity challenge was the introduction of a transition layer with high thermal conductivity adjacent to thin electric heaters, which significantly improved the spatial uniformity of cavity temperature distribution.

The biomedical field has been a particularly active domain for microinjection moulding research and application. Specialized mold designs have been developed for manufacturing biodegradable polylactic acid (PLA)-based microneedle arrays intended for transdermal drug delivery, incorporating drug-loaded channels in the microneedle structure. Processing of polydioxanone (PDO), a resorbable polymer used in surgical sutures, stents, and small implants, by microinjection moulding has been demonstrated to yield specimens with high dimensional uniformity and shape stability. The technique has also been applied successfully to the fabrication of small-module plastic gears with submillimeter tooth profiles, light guide plates for liquid crystal displays, and precision optical elements.

4.6 Rapid Thermal Cycling Moulding (RTCM)

Rapid thermal cycling moulding takes the principle of variable mold temperature to its most dynamic expression, deliberately cycling the mold surface temperature between a high value, near or above the glass transition temperature (Tg) or melting temperature of the polymer, during filling and packing, and a low value during cooling. The rationale is straightforward: maintaining an elevated mold surface temperature during melt flow eliminates the frozen layer that forms at a cold mold wall, allows complete replication of fine surface features, eliminates weld lines that would otherwise result from the premature freezing of flow fronts, and produces surface finishes approaching optical quality without post-moulding polishing. Rapid cooling after the packing phase then restores cycle time competitiveness.

The molecular mechanism underlying RTCM's superior surface replication was elucidated by [10] Zhang and co-workers, who showed that the elevated mold temperature maintained for an extended period ensures that Brownian motion remains active in the polymer surface layer, enabling the melt to conform precisely to mold surface features at the nanoscale. This mechanism explains why RTCM produces surfaces that appear optically identical to the mold surface even when the latter carries micro- or nanoscale texture features.

Warpage in crystalline polymers remains a challenge in RTCM, since the rapid thermal cycle alters the crystallization kinetics relative to conventional moulding, potentially producing non-uniform crystallinity across the part cross-section. Multivariate predictive models for warpage have been developed specifically for RTCM conditions. Research into graphene-based carbide coatings as thin-film heating elements for RTCM demonstrated heating rates up to 16.1°C/second at 240 V, enabling the mold cavity to reach 145.6°C in just 10 seconds. The mechanical properties of parts produced with this coating showed improvements of 37.77% in tensile strength and 256.11% in elongation at yield, with significantly reduced energy consumption compared with conventional electric resistance heating.

4.7 Multicomponent Injection Moulding

Multicomponent injection moulding encompasses a family of processes in which two or more different polymers or the same polymer in different colors are injected into a single mold during the same moulding cycle to produce a finished part composed of distinct material zones. This capability opens up product design possibilities that are unachievable by any single-material process: components with a rigid structural core and a soft-touch elastomeric surface, parts with multiple colors moulded in a single step, or assemblies in which different regions have fundamentally different thermal or electrical properties. The elimination of secondary bonding or assembly operations reduces manufacturing cost and potentially improves the reliability of the interface between material zones.

In insert-over-moulding, a preformed component of the first material is placed in the mold and the second material is injected around it. In sequential two-shot moulding, the mold incorporates a rotating platen or movable core that repositions the first-shot part to receive the second injection. [30] Park and colleagues demonstrated the feasibility of layered multicomponent moulding using a co-injection machine with a maximum injection pressure of 175 MPa, supported by numerical simulations that confirmed the experimentally observed material distribution.

The multicomponent approach has been particularly successful in producing flame-retardant parts, since a fire-resistant skin material can be applied over a core that delivers the required structural properties without carrying the full flame retardant loading throughout the part. Production of nanocomposites reinforced with carbon fiber and carbon nanotubes using resin transfer moulding has also been demonstrated in a multicomponent context, yielding tensile strengths of 303 ± 41 MPa. Among the most commercially significant applications of multi component moulding are automotive exterior and interior trim components, swimming goggles, protective equipment, and sports equipment such as table tennis racket handles.

4.8 Metal Injection Moulding (MIM)

Metal injection moulding extends the principles of conventional polymer injection moulding to the production of small, geometrically complex metal components with dimensional tolerances and surface finishes that machining alone would find difficult or uneconomical to achieve. The feedstock for MIM is a mixture of fine metal powder, typically with particle sizes in the range of 5 to 20 micrometers and a multi-component binder system comprising polymers, waxes, and processing aids. This feedstock behaves rheologically as a viscous suspension and can be injected into precision molds on equipment resembling conventional plastic injection machines. After moulding, the binder is removed by a combination of solvent extraction and thermal debinding, and the resulting brown part is sintered to near-full density.

The binder formulation is among the most critical variables in MIM process development, since it must simultaneously provide adequate flow properties during injection, structural integrity in the green state, and clean, residue-free removal during debinding. [31] Royer and associates investigated a novel bio-sourced binder for Inconel-718 super alloy MIM feedstock based on polyhydroxyalkanoates (PHA) and poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) in combination with polyethylene glycol. This work demonstrated that the biologically derived PHBV could successfully replace polypropylene in conventional binder formulations while maintaining similar rheological properties and achieving a higher maximum volume fraction of metal powder — a result with positive implications for both sustainability and part density.

Application-specific MIM research has been conducted in several industrially significant areas. The processing of magnesium alloys for biomedical implant applications demonstrated that sintered Mg-0.9Ca parts achieve tensile strength of 142 MPa, yield strength of 67 MPa, elastic modulus of 40 GPa, and 8% elongation — properties comparable to cast material.

4.9 Reaction Injection Moulding (RIM)

Reaction injection moulding occupies a conceptually distinct position from all other techniques discussed in this review, in that the part material is not pre-formed as a solid thermoplastic but is instead synthesized within the mold cavity itself through the rapid reaction of two or more liquid reactive components injected simultaneously. Most commonly, RIM is applied to polyurethane systems, in which a polyol component and an isocyanate component are mixed at high velocity in an impingement mixing head immediately before injection. The exothermic polymerization reaction proceeds within the mold to produce a fully polymerized part in a relatively short cycle time, depending on formulation reactivity.

[32] Gomes and colleagues proposed the use of differential static pressure between the two injected monomer streams as a parameter for controlling mixing quality, demonstrating a correlation between this pressure differential and the mechanical properties of the moulded part. [33] Yacoub and MacGregor brought multivariate statistical methods, specifically principal component analysis (PCA) and projection to latent structure (PLS), to bear on the analysis of a polyurethane RIM process, revealing the underlying mechanisms linking process variables to product quality and identifying the sources of processing problems.

Research by [34] Lehmenkühler and Stommel on the effect of RIM process conditions on the thermomechanical properties of fast-curing polyurethane showed that a 20°C increase in mold temperature increases Young's modulus by approximately 2% and necking stress by 3%, while increasing mass flow rate and temperature together produces further improvements in stiffness.

5. Applications of Advanced Injection Moulding Technologies

- Manufacturing lightweight automotive components such as dashboards, interior panels, air ducts, and structural parts.
- Production of aerospace components requiring high dimensional accuracy and reduced weight.
- Fabrication of medical products including syringes, diagnostic device components, surgical instruments, and microneedle systems.
- Production of electrical and electronic components such as housings, connectors, switches, and insulation parts.
- Manufacturing of packaging products including containers, caps, closures, storage boxes, and protective packaging materials.
- Production of consumer goods such as toys, household items, furniture components, and sporting equipment.
- Fabrication of lightweight composite foams with improved thermal insulation and sound absorption properties.
- Development of high-precision microcomponents for medical, optical, and microengineering applications through microinjection moulding.
- Manufacturing of hollow plastic products using water-assisted and gas-assisted injection moulding technologies.

- Production of aesthetically superior products with improved surface finish through advanced mold temperature control technologies.
- Reduction of material consumption, product weight, and energy usage while maintaining product quality and production efficiency.
- Support for sustainable manufacturing through improved resource utilization and reduced environmental impact.

6. Conclusions

This review has documented the remarkable breadth and depth of innovation that has reshaped injection moulding technology over recent decades. From a process originally limited to simple solid thermoplastic parts, injection moulding has evolved into a sophisticated family of techniques capable of producing hollow tubular structures (WAIM, GAIM), microcellular lightweight foams (MIM), components with mirror-finish surfaces and zero weld lines (RTCM), multi-material assemblies in a single moulding cycle (multicomponent IM), complex small metal components (metal IM), and reactively polymerized structural parts (RIM) among many other accomplishments.

Several overarching conclusions emerge from the synthesis of the research literature. First, process parameters, particularly melt temperature, mold temperature, injection pressure, and cooling time, exercise a decisive and often interactive influence on product quality across all moulding techniques; parameter optimization, increasingly pursued through statistical design of experiments and numerical simulation, is therefore an indispensable element of competent process engineering. Second, the choice of material interacts closely with the choice of technique: properties such as crystallinity, melt viscosity, and thermal sensitivity determine which advanced techniques are appropriate for a given polymer, and how they must be adapted. Third, sustainability considerations — encompassing energy efficiency, material utilization, recyclability, and lifecycle impact — are no longer peripheral to injection moulding process development but are becoming central criteria in technology selection and optimization.

7. Future Scope

Despite the considerable advances documented in this review, several important research gaps and development opportunities remain open. The following directions are identified as particularly consequential for the near-term evolution of injection moulding technology.

1. **Smart Process Control:**

   The established influence of melt temperature, injection pressure, and cooling time on the mechanical and dimensional properties of injection-moulded parts, confirmed across PP, PE, ABS, and other polymers, provides a ready foundation for closed-loop adaptive control systems. Future work should translate these quantitative process-property relationships into real-time controllers and digital twin models capable of adjusting parameters on a shot-by-shot basis, reducing scrap and shortening mold qualification cycles.

2. **Sustainable and Recyclable Materials:**

   The finding that PLA injection moulding consumes approximately 38.2% less energy per kilogram than fused deposition modeling underlines the environmental competitiveness of the injection route even for biobased polymers. Extending rigorous lifecycle comparisons to natural fiber composites, including rice husk-filled and buckwheat hull-reinforced polypropylene systems already demonstrated as processable and developing robust multi-generation reprocessing protocols for commodity and engineering thermoplastics are priorities for a field facing growing regulatory and market pressure on sustainability.

3. **Additive Manufacturing for Mold Tooling:**
   Conformal cooling channels fabricated by additive manufacturing have already reduced cooling time by up to 30%, and this approach has not yet been fully exploited across the diversity of mold geometries encountered in practice. Functionally graded and porous mold inserts, architectures achievable only through additive fabrication, represent the next tier of tooling innovation, with potential benefits for RTCM heating uniformity, surface finish, and mold life.

4. **Microinjection Moulding for Medical Devices:**
   Biodegradable micro needle arrays, resorbable PDO implant components, and precision micro-gears produced by microinjection moulding demonstrate the technique's reach into high-value medical and optical applications. The frozen layer challenge — partially addressed through gas-assisted internal heating that raised fill completeness from 65.4% to 100% — must be systematically resolved across the full range of biocompatible and bioresorbable polymers before microinjection moulding can be considered a mature production route for regulated medical devices.

5. **Automation and Industry:** Fully autonomous injection moulding cells, combining collaborative robotics, in-line vision inspection, and machine learning-based process control, remain a significant engineering target. The quantitative process-property knowledge accumulated in the injection moulding research literature provides the structured domain knowledge that data-driven control systems require to generalize reliably, and its translation into deployable industrial automation represents one of the field's most commercially consequential open challenges.

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