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RECENT PROGRESS IN MATERIALS, PROCESSING, REAL-TIME SENSING AND COOLING STRATEGIES IN PLASTICS TECHNOLOGY

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Abstract

Plastics technology has seen rapid advancements in recent years, with a focus on optimizing material properties, molding techniques, and performance parameters. This review systematically delves into the intricacies of these areas, offering a critical assessment of diverse molding methods and their subsequent implications on performance. Emphasis is placed on novel approaches and material breakthroughs, elucidating their potential applications and environmental consequences. The narrative seamlessly shifts to processing, accentuating the paramount importance of optimization strategies and stringent quality control measures. The transformative potential of integrating real-time sensing and monitoring technologies is underscored, highlighting their pivotal role in enhancing process efficiency. A central component of this review is the exploration of cooling in plastics technology, specifically emphasizing the design, fabrication, and performance optimization of conformal cooling channels. By amalgamating insights from these domains, this review aims to serve as a holistic guide for both academia and industry, fostering informed decision-making in research and real-world applications. The review concludes by sketching potential future directions in plastics technology, offering a panoramic view of the impending innovations. In synthesizing the wealth of knowledge in these areas, this review aims to provide a coherent framework for academics and industry professionals , facilitating informed decision-making in research and applications. Potential future trajectories in plastics technology are also briefly touched upon, offering a glimpse into the horizon of possibilities.

Keywords: Plastics Technology, Material, Processing, Real-time sensing, Cooling, Conformal Cooling, Optimization

1. Introduction

Plastics have long been an integral part of modern life, offering versatility, durability, and cost-effectiveness in a myriad of applications. Over the years, the plastics industry has witnessed significant advancements in materials, processing techniques, and cooling strategies, driven by the need for sustainable solutions, improved performance, and enhanced environmental compatibility. This introduction delves into the recent progress in these areas, drawing insights from cutting-edge research. The evolution of plastic materials has been marked by a continuous quest for innovation. One of the promising areas of research has been in the domain of bio-based plastics composites [1]. Processing techniques have also seen remarkable advancements. Severe plastic deformation, for instance, offers the potential to produce materials with nanocrystalline or nanocomposite structures, broadening their applicability in various industrial sectors [2]. The significance of such advancements is the superior properties of nanostructured materials produced by severe plastic deformation, making them particularly attractive for sectors like aerospace and biomedicine [3].Cooling strategies in plastics technology play a pivotal role in determining the physical stability of the materials, the rate of cooling significantly influences the stability of plastic materials. This is crucial as the physical properties of plastics, such as their strength, flexibility, and transparency, can be greatly affected by the cooling rate during processing. As we continue to prioritize sustainability and performance, the advancements in materials, processing, and cooling strategies promise a future where plastics not only meet our functional needs but also align with our environmental and ethical values. The processing of plastics has undergone significant transformation, with the integration of innovative techniques that not only enhance the quality of the final product but also contribute to a more sustainable plastic economy. This approach not only aids in the efficient recycling of plastics but also underscores the potential of integrating established techniques from other industries into plastics processing.

The cooling phase in plastics processing is pivotal, as it significantly influences the final properties of the plastic product. Recent advancements in cooling strategies have been driven by the need for energy efficiency, improved product quality, and sustainability. These strategies have been tailored to cater to specific applications, from electronic devices to greenhouse coverings, and have been instrumental in enhancing the overall performance and efficiency of plastic products. Such insights are crucial for industries that rely on injection molding for producing high-quality plastic components. Innovative cooling designs have also been introduced to reduce the cycle time of plastic parts. For instance, the application of new triple hook-shaped conformal cooling channels has resulted in a 32.61% reduction in cycle time compared to traditional cooling geometries [4]. This not only enhances the production efficiency but also contributes to significant economic and energy savings.

In the rapidly evolving field of plastics technology, the integration of advanced materials, innovative processing techniques, and efficient cooling strategies has been at the forefront of research and development. While significant strides have been made in each of these areas, there remains a research gap in the holistic integration of these advancements to achieve optimal performance, sustainability, and cost-effectiveness. The novelty lies in the exploration of synergistic effects when these advancements are combined. Addressing these gaps can lead to the development of next-generation plastic products that are not only superior in quality but also environmentally friendly and economically viable.

2. Material

In the ensuing discourse, a thorough examination of material science is undertaken, with a particular emphasis on the fundamental elements that constitute the underpinnings of a myriad of industries and practical applications. Materials, in their diverse forms, serve as the quintessential building blocks of the tangible world, profoundly influencing a plethora of domains from architectural structures and technological devices to apparel.

2.1 Material Properties and Performance

Delving into a diverse spectrum of molding techniques, mechanics of powder molding and exploring innovative techniques such as spark plasma sintering, electromagnetic-assisted molding, and Graphene composites as shown in Fig. 1. This study navigates the confluence of molding methods, aligning them meticulously with raw material properties and anticipated end-products, thereby providing valuable guidelines for the selection of appropriate molding methods corresponding to specific material properties and desired outcomes.

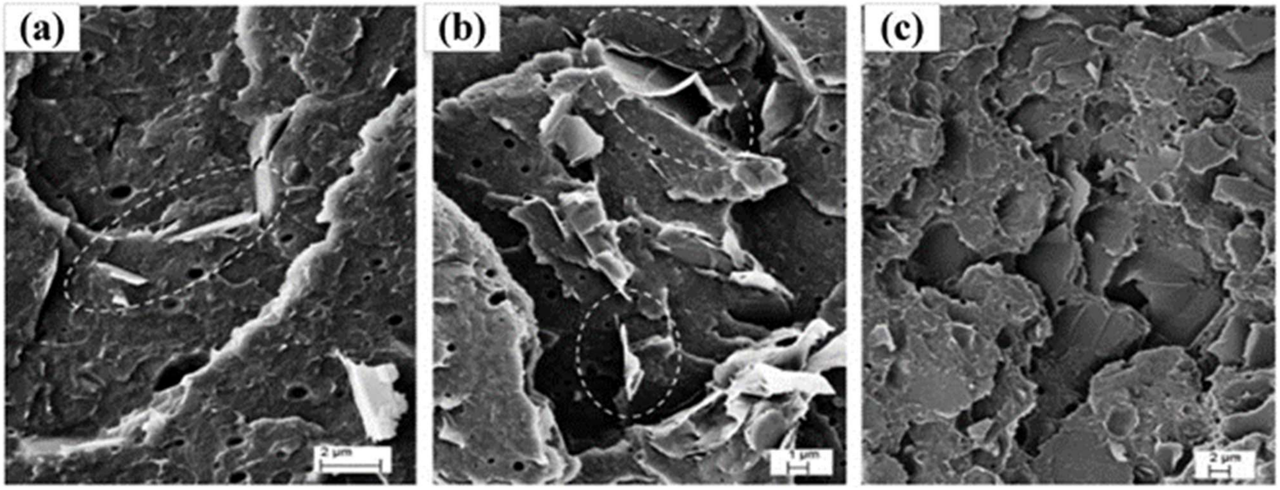


Fig. 1 Graphene composites:20 (a) 4-H; (b) 4-V; (c) 4-P [5].

Further, research accentuates the influence of diverse molding conditions on the physical aging of polystyrene injection moldings. It was unveiled that the molecular orientation of materials is susceptible to alterations, contingent on the injection rate and holding pressure. Remarkably, surface molecules exhibit resilience to relaxation under heat treatment beneath the glass transition temperature (Tg), suggesting their elongation during the filling stage, whereas core molecules may experience orientation during the holding stage [6]. New study, a pivotal study provides enlightening revelations concerning the relationship between molecular weight and the expansion properties of resins. It was discerned that resins with elevated molecular weight and assorted chain lengths manifested enhanced expansion, attributable to elevated crystallization temperatures and augmented stretching behaviours as shown in Fig.2.In contrast, resins with reduced molecular weight exhibited superior cellular initiation and denser foam structures, thereby delineating a structured framework for the meticulous selection and crafting of resins, spotlighting the crucial factors governing expansion and cellular inception [7].

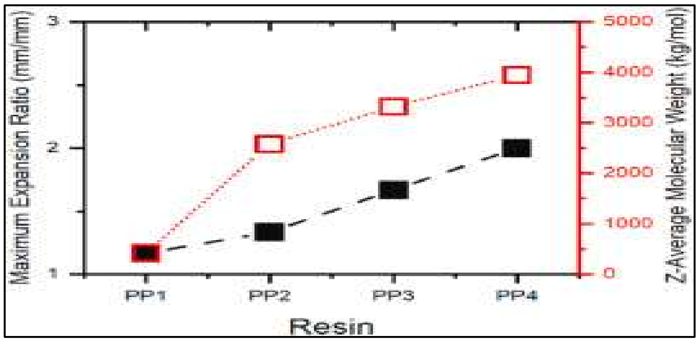


Fig. 2 Maximum expansion ratio achieved at 0.5 s packing time (solid black squares) and z-average molecular weight (hollow red squares) for each resin [7].

Research exploring the intricate relationships between polymers, metals, and other compounds, focusing on their mechanical, thermal, and environmental properties, as well as their performance characteristics under varying conditions. One study investigates the impact of polymer type on the joint strength of polymer/copper hybrids fabricated via nano-injection molding, comparing polybutylene terephthalate (PBT) and polyphenylene sulphide (PPS) through both experimental and computational lenses. The findings reveal a heightened joint strength in PPS/copper hybrids, averaging 90.639 MPa, as opposed to PBT/copper hybrids, which demonstrate an average strength of 77.14 MPa [8]. A detailed analysis employing scanning electron microscopy, differential scanning calorimetry, and numerical simulations unveils the correlation between thermal properties and crystallization behaviour of compounds as shown in Fig. 3. The study concludes that elevated thermal conductivity corresponds to expedited cooling and diminished crystallinity, impacting the compounds mechanical properties. It is also disclosed that boron-nitride operates as a nucleating agent at reduced cooling rates, its efficacy waning at accelerated rates [9].

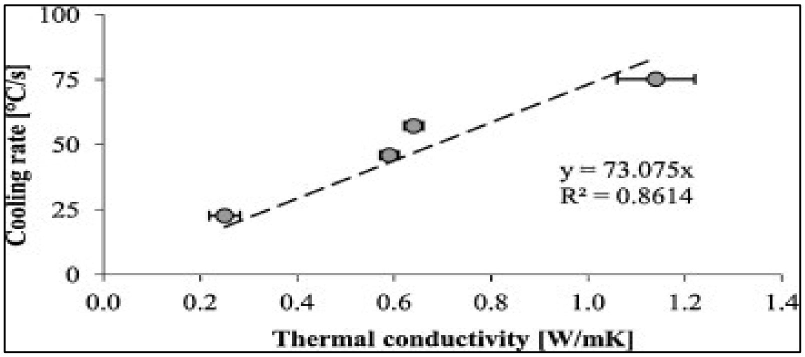
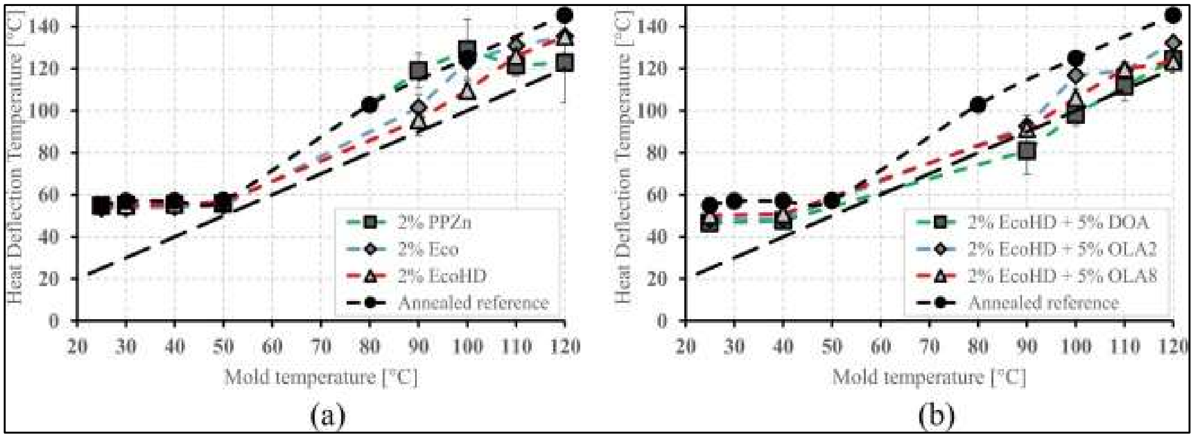


Fig. 3 Relationship between the cooling rate and the thermal conductivity of the compounds [9]

Exploration into the effect of nucleating agents, plasticizers, and molding conditions on the properties of injection molded PLA products reveals superior heat deflection temperature, tensile strength, and Young's modulus in PLA modified with nucleating agents compared to Acrylonitrile Butadiene Styrene (ABS) as shown in Fig. 4. Nonetheless, the elongation at break for annealed and simultaneously nucleated and plasticized PLA compounds lags significantly behind that of ABS [10].



(a) (b)

Fig. 4 Heat deflection temperature of 3100HP grade PLA nucleated with 2 wt% PPZn, Ecopromote, and EcopromoteHD (a) and nucleated with 2 wt% EcopromoteHD and plasticized with 5 wt% DOA, OLA2, and OLA8 (b) as a function of mold temperature. The long-dashed line represents the same mold temperature and HDT values [10].

Insight into the environmental resilience of a PLA and SEBS-g-MA blend unveils its sustenance of shape memory performance upon exposure to water at 60°C. However, a decline in tensile strength is noted in additively manufactured samples initially superior to injection-molded samples likely due to augmented moisture absorption [11]. New study,on the enhancement of toughness in poly (L-lactic acid) (PLLA) based blend composites using carbon nanofibers (CNFs) highlights the formation of a "mutton kebab"like structure, occurring due to the self-assembly of CNFs and poly (butylene adipate-co-butylene terephthalate) (PBAT) particles. This structure bolsters interfacial interaction, catapulting the toughness by 270% when the PLLA crystallinity is approximately 32.6% [12]. Study synthesizes diverse studies, each contributing nuanced insights into the optimization and characterization of polymers and their composites under varying conditions and compositions. A notable study employs a meticulous decision-making technique to optimize marble dust-filled polymer composites, with the assessment of PLA and pet composites revealing that 10 wt% marble dust-filled PLA composite ranks superiorly and aligns with validations from alternative methods [13]. Another innovative exploration investigates the efficacy of terpenoid-based organic compounds as plasticizers for Poly(3-hydroxybutyrate) (P3HB). The incorporation of geranyl acetate resulted in a substantial 31.1% augmentation in the elongation at break of P3HB, a reduction in glass transition temperature, and an expedited disintegration rate in compost soil, showcasing the potential for enhancing ductility and environmental compatibility [14]. This study amalgamates the findings from numerous studies, each delving into distinct aspects of polymer composites and their multifarious properties. One pivotal study highlighted the analysis of LDPE/Surlyn blends, prepared through extrusion and characterized by diverse parameters including melt flow index, morphology, and mechanical and thermal properties. The incorporation of Surlyn into the blends was found to enhance tensile and flexural strength, stiffness, and strain at break, albeit at the expense of reducing impact strength and heat deflection temperature [15]. Another study delved into the structural heterogeneity and evolution in ultrahigh-filled polypropylene/flake graphite composites during injection molding. The research discovered that a specific PP/FG composite, PP/FG (30/70), demonstrated a pronounced discrepancy in thermal conductivity between the distal and proximal ends, a difference that can be accentuated by the addition of spherical alumina (Al2O3) microparticles at an optimal concentration of 2.5 wt% [16]. Further, innovative research explored the fabrication of lightweight, high-impact polypropylene (PP) foam through the utilization of a novel foam injection molding (FIM) technology, necessitating ultra-low nitrogen pressure. The integration of a polyolefin elastomer (POE) component yielded a PP/POE foam with an exquisite cellular structure characterized by minute cell size and elevated cell density. This structural refinement resulted in an astounding 465% enhancement in impact performance in comparison to its pure PP foam counterpart [17]Review synthesizes various explorations into the nuanced interplays between polymer composites, their processing parameters, and resultant properties. One distinctive study examined HDPE gears produced at divergent mold temperatures and tested under varying torque loadings. A suite of analysis techniques, including DSC, SEM, and LVDT, were deployed to scrutinize peak melting points, crystallinity, wear rates, modes of failure, and debris formation of the gears. The findings from this study illuminated that elevated mold temperatures contribute to an augmentation in crystallinity, albeit with a concomitant diminution in toughness. This nuanced interplay led to the emergence of distinct wear mechanisms and failure modes, contingent on the specific torque loadings [18]. Subsequently, another paper meticulously reported on experimental outcomes derived from 27 trials utilizing transparent thermoplastic polypropylene material. This exhaustive exploration revealed that an optimal parameter setting encompassing a melt temperature of 240°C, mold temperature of 40°C, packing time of 8 seconds, a rib to wall ratio of 65%, and a rib to gate distance of 65 mm could substantially mitigate the sink mark depth to 0.24 mm, heralding enhancements in both product quality and productivity [19]New study, intricate research into the structural evolution of isotactic polypropylene (iPP) under micro-injection molding, with variations in mold temperatures and molecular masses, unveiled the consistent emergence of shish-kebab patterns and parent-daughter layers across all iPP specimens during the molding progression as shown in Fig. 5. A noteworthy observation was the pronounced augmentation in the extent of the shish structures at the inception of crystallization, a phenomenon modulated by the concurrent mold temperature [20].

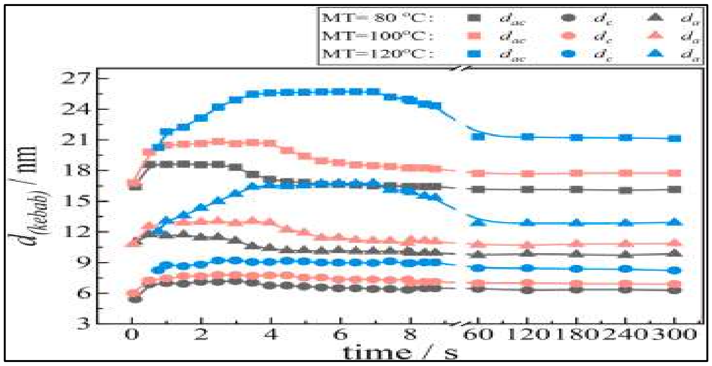


Fig. 5. Change of dac, dc, and da of the kebab lamellae with crystallization time taken at different mold temperatures [20]

In a meticulous exploration of molding techniques and their influences on polymer characteristics, extensive research focused on the impacts of mold opening on microcellular polyether-ether-ketone (PEEK) synthesized via injection molding. The study unearthed that the innovative mold-opening microcellular injection molding (MOMIM) technique allowed for the crafting of microcellular PEEK, culminating in a substantial reduction in weight of approximately 49.6%. This research extended its exploration to analyse the effects of varying parameters including holding duration, applied pressure, and the degree of mold opening on this specialized form of PEEK. The empirical observations underscored those enhancements in both the holding duration and the pressure applied contributed to an increase in PEEK's density and fostered the development of more compact cell structures, thereby augmenting its mechanical strengths as shown in Fig. 6 [21].

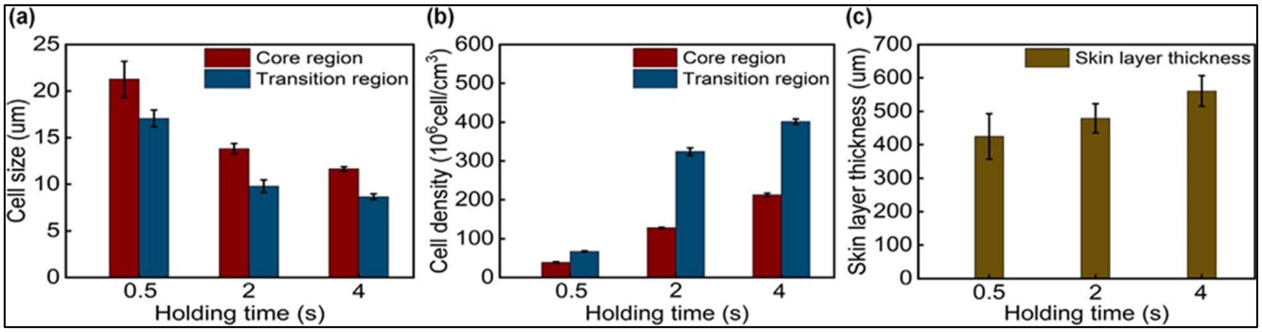


Fig. 6. Quantitative cell information of microcellular PEEK under different holding times: (a) cell size, (b) cell density, and (c) skin layer thickness [21]

Simultaneously, another study, leveraging molecular dynamics simulations, delved into the behaviour of polybutylene terephthalate (PBT) within diverse nanopores. The study concentrated on examining various attributes such as filling rates, depths, interfacial energy, and the dynamics of polymer chains as shown in Fig 7. The insights gleaned revealed that PBT, with varying molecular weights, exhibited the capability to infiltrate deeply into nanopores, achieving remarkable filling rates of up to 90%. Furthermore, the dimensions of the nanostructures were identified as significant determinants influencing the interactions and entwinements of the polymer chains [22].

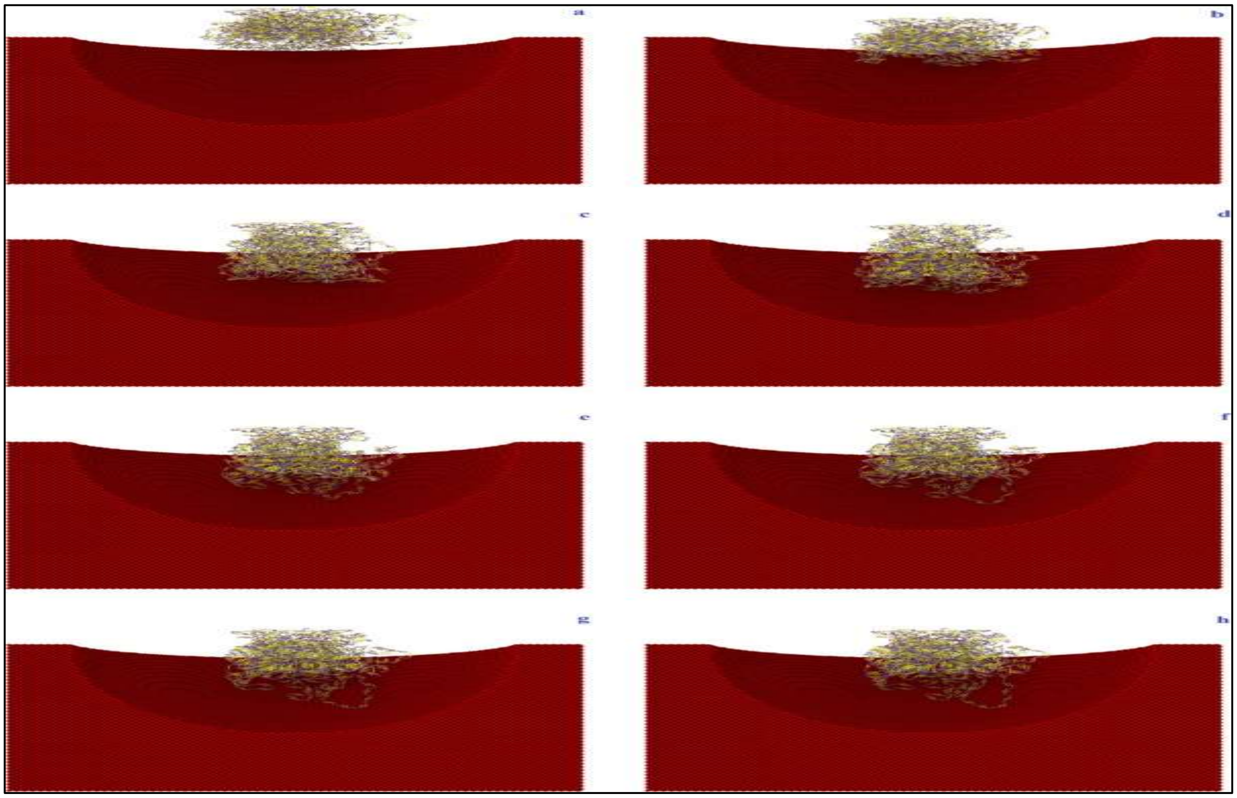


Fig. 7. Flow behaviour of polymer chains (Mw = 170,235 g/mol; diameter of big pores: 202.435 Å; a–h: 0, 5, 10, 20, 35, 45, 115, and 185 ps, respectively) [22].

In the vast landscape of product development, the choice of material plays an indispensable role, influencing both design and function. A specific study underscores the superior creep performance of injection-molded samples. However, certain infill densities and directions in FDM samples also showcase commendable creep resistance under elevated stress levels. Theoretical predictions deployed in this study, specifically the Burgers and Weibull's models, exhibit varying accuracy levels, with Weibull's model reflecting a refined average mean absolute percentage error of 3.44%[23]. Delving into a diverse spectrum of molding techniques, another seminal article serves as an extensive repository of knowledge, elucidating the mechanics of powder molding and exploring innovative techniques such as spark plasma sintering and electromagnetic-assisted molding. This study navigates the confluence of molding methods, aligning them meticulously with raw material properties and anticipated end-products, thereby providing valuable guidelines for the selection of appropriate molding methods corresponding to specific material properties and desired outcomes [5].

2.2 Specialized Techniques and Novel Approaches

Study encapsulates a spectrum of innovative studies, each elucidating distinct aspects of material fabrication, composite strengthening, and quality enhancement in injection molding processes. A novel study explored the potential of an innovative laser scanning strategy employing a continuous-wave (CW) fibre laser, which is pivotal in fabricating deep grooves rapidly in diverse materials. When integrated into metal-plastic hybrid (MPH) joinery, this strategy manifested a notable enhancement in joining strength, as validated by lap shear tensile tests [24]. Simultaneously, another research endeavour introduced a sophisticated rule-of-mixtures model designed to predict the strength at the melding line of injection-molded, short-glass-fibre-reinforced polycarbonate compounds. This model, correlating composite strength with the sectional fraction of outer and inner layers, meticulously incorporates factors such as fibre length, alignment, volume fraction, and bond strength between fibre and matrix. Remarkably, the model's predictions exhibit substantial congruence with empirical findings across varied fibre densities as shown in Fig. 8 [25].

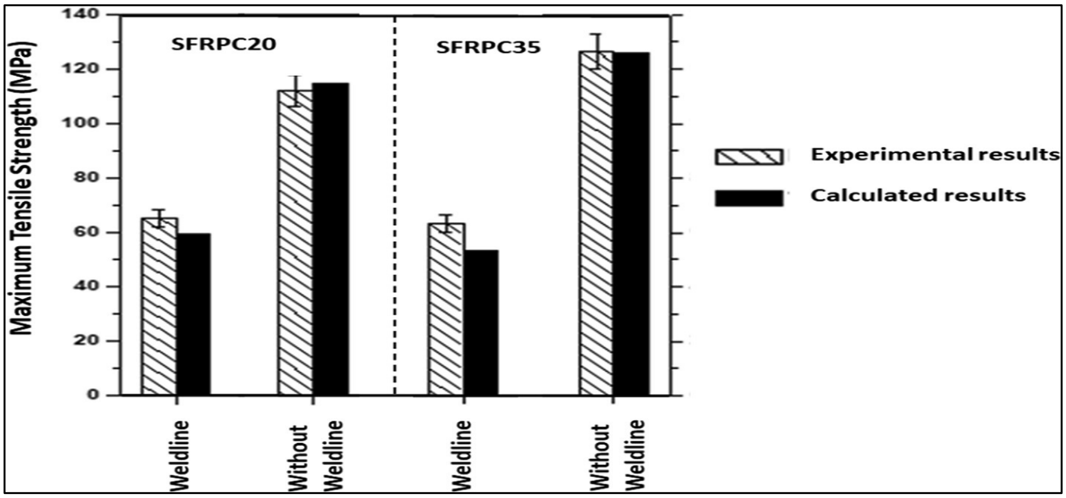


Fig.8 Comparison of experimental and theoretically calculated weld line strength for tensile specimens of 20 and 35%wt short-glass-fibre reinforced polycarbonate [25]

In a pursuit to enhance material integration, a study deployed an incubator device, coupled with a meta-heuristic algorithm, the WSA, to optimize the amalgamation of plastic waste and alumina nanoparticles within an injection flow mechanism (IFM). The method not only reduced defects by 23.21% but also amplified system performance by 70.98%, marking a significant advancement in composite preparation methodologies [26]. Further, research into impact performance prediction of composite wheels revealed an enhanced co-simulation method, substantiated by fabricating and testing long-glass-fibre reinforced polyamide 66 composite wheels, displaying evident superior calculation accuracy compared to pre-existing co-simulation methods [27]. New study, a comprehensive overview of research and development in injection molding focused on the optical aspects of surface quality and defects, providing insights into measurement, influencing factors, prediction, and control of surface quality and defects, and delineating prospective research avenues for the refinement of surface appearance in injection-molded products as shown in Fig 9 [28].

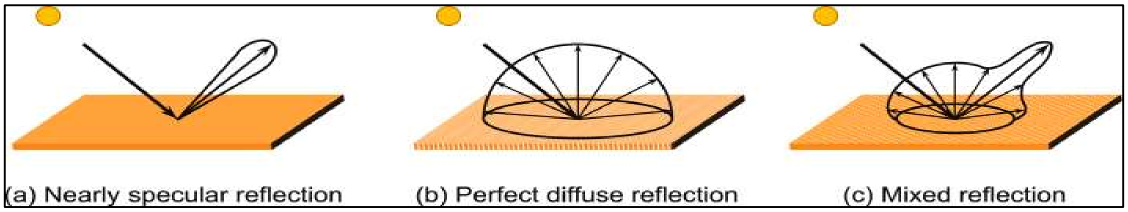


Fig. 9 Examples of BRDF for various surfaces and refractive index, (a) nearly specular reflection at high gloss surface, (b) perfect diffuse (Lambertian) reflection at low gloss surface, (c) mixed reflection at semi-gloss surface [28]

Further, a detailed framework is proposed for predictive maintenance in the injection molding process, incorporating data from diverse sources and utilizing both edge and cloud computing systems. Demonstrated by a case study focusing on cooling system monitoring and mold temperature prediction using machine learning models, the framework yielded an average error of 3.29% in mold temperature prediction, showcasing its potential in detecting cooling discrepancies using varied process data [29]. Moreover, a unique method, grounded in morphological surfaces, the inverse heat conduction problem, and the conjugate gradient algorithm, is applied to determine the location, shape, and temperature of the cooling channels in a 3D industrial part. The comparative analysis with conventional cooling systems revealed the proficiency of the proposed method in enhancing process quality and efficiency by minimizing temperature gradients and attaining the desired ejection temperature in the part [30]. Study shoes the insights on enhancing the understanding of heat transfer dynamics from polymer melts within an injection mold. The study propounds a novel equation, meticulously derived from an in-depth analysis of heat transfer phenomena, and conducts a comparative assessment with pre-existing equations, employing three commonly used plastics: ABS, PC, and PP. The outcomes of this comparative analysis corroborate that the newly developed equation aligns proficiently with previously reported data in the academic literature. Importantly, the study underscores a pivotal insight, elucidating that leveraging an average temperature spanning the cross-section of the molded part as the ejection temperature emerges as a more pragmatic approach compared to the application of the mid-plane temperature.[31]. The versatility of Foam Injection Molding (FIM) has been explored to process diverse ceramic feedstocks, enabling the fabrication of samples possessing varied geometries, high complexity, and enhanced functionality. Study evaluated the quality of the ceramic parts based on several parameters including microstructure, density, shrinkage, shape distortion, defects, and piezoelectric performance. It also addressed the challenges and proposed solutions for optimizing FIM process parameters, focusing on aspects like injection molding simulations, mold design, and de-molding strategies as shown in Fig. 10 [32].

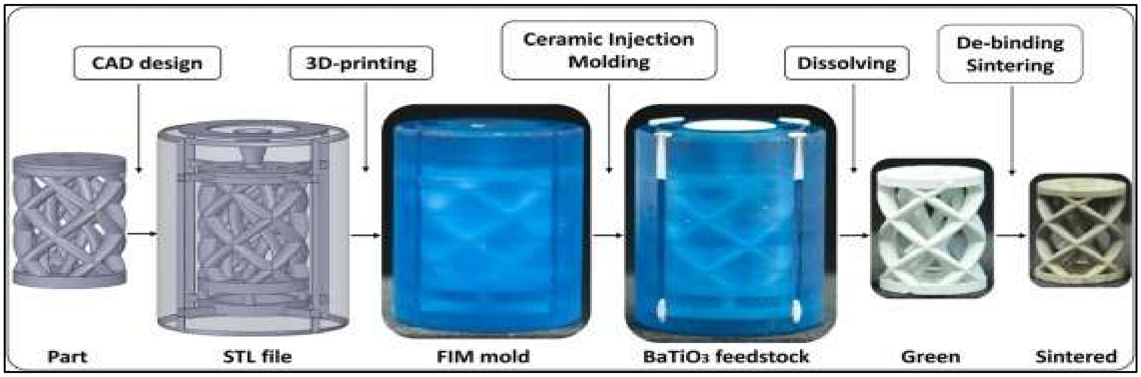


Fig. 10 The FIM process steps exemplified by fabricating a ceramic double helix (BaTiO3). The CAD model of the part and the design of the FIM mold before it is 3D-printed, injection-molded and dissolved, and finally, de-binding and sintering of the ceramic part [32]

Additionally, a study introduced a cost-effective injection molding tool designed specifically for the rapid prototyping of ultra-precise components, such as polymer-based drug dispensers and microneedle arrays. The authors developed a prototype injection molding mechanism that can produce uniquely-shaped parts using swappable insert molds made from epoxy or resin derived from 3D printers, presenting a pioneering approach in the realm of precision components manufacturing as shown in Fig. 11 [33].

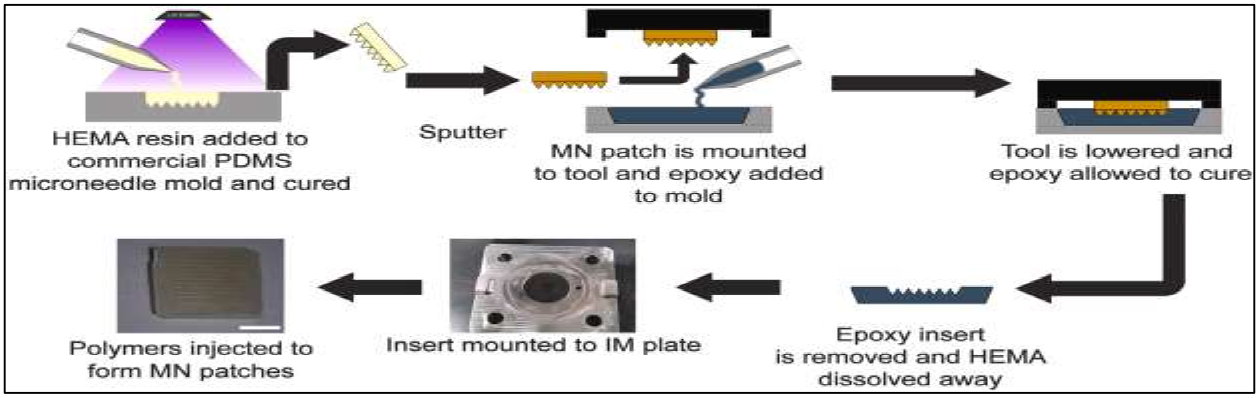


Fig. 11. Diagram describing the procedure for fabricating IM microneedle patches. Scale bar: 3 mm [33]

The progression in the field of injection molding and materials science is well reflected through various studies, each exploring different facets of materials and molding processes. One study in particular, delved into the assessment of surface energy of distinct mold materials within the context of low-pressure powder injection molding. This study investigated the correlation between feedstock moldability and mold adhesion. The experimental results revealed a crucial insight, emphasizing that the interfacial energy between the mold and binder plays a pivotal role in determining adhesion. Remarkably, metallic molds exhibited lower adhesion in comparison to their polymeric counterparts. The study also demonstrated that the adhesion phenomenon is exclusively linked to the properties of mold surface, rather than the rate of solidification [34]. Another research study engaged in a detailed characterization of the mechanical properties and microstructure of stainless steel 316L (SS 316L) fabricated through metal powder injection molding (MIM), a technique renowned for its capability to create intricate metal parts embodying high strength and precision as shown in Fig. 12. The authors orchestrated a comparative analysis between MIM SS 316L and its cold-rolled and hot-rolled counterparts, exploring aspects such as density, tensile strength, fatigue life, grain size, and deformation behaviour, thereby providing comprehensive insights into the structural integrity and mechanical properties of the materials [35].

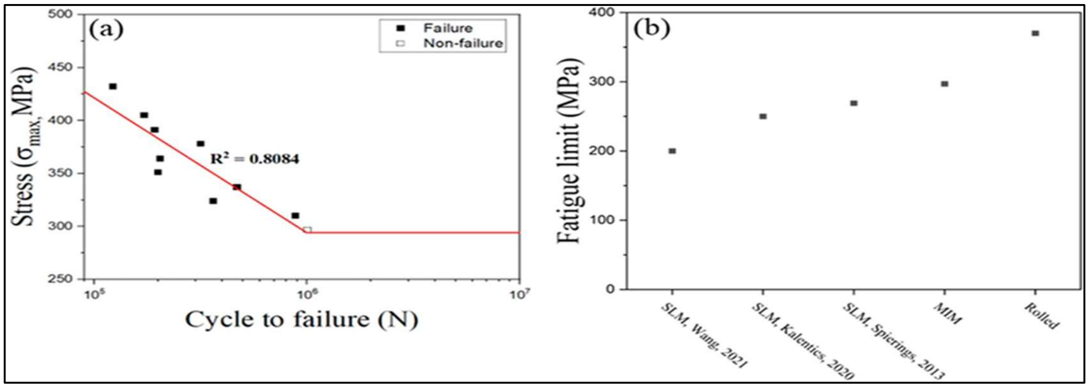


Figure 12. (a) Stress–life curve of SS 316L produced by metal powder injection molding. (b) Fatigue limit measurement results reported in the literature and in this work for SS 316L [35]

Additionally, a study proposing a novel hybrid joining technique, specifically designed for polymer and galvanized high-strength steel (GHSS), leveraging the principles of injection molding. This research highlighted the effectiveness of hot water treatment (HWT) in inducing a nanoscale needle-like structure on the zinc coating surface, a transformation that significantly enhanced joining strength. The optimization of this method resulted in achieving a joining strength of 23 MPa, with mechanical interlocking identified as the principal factor contributing to the elevated joining strength as shown in Fig.13 [36].

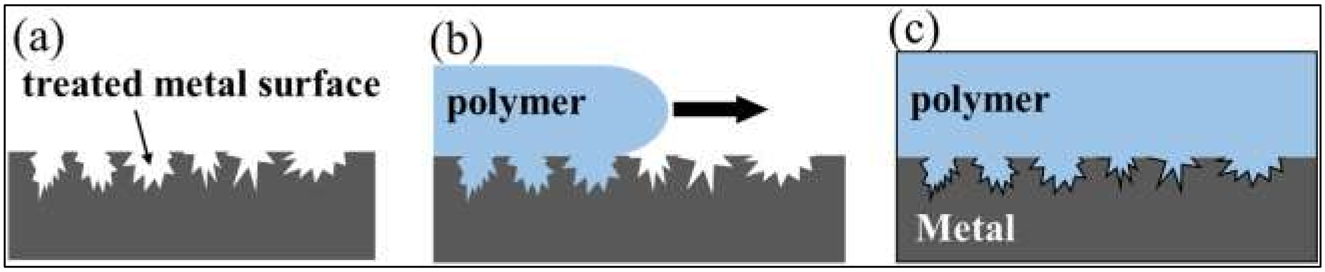


Fig. 13. IMDJ process: (a) micro/nano structures are formed on metal surface; (b) melted polymer flows into the surface structures during injection molding process; (c) metal and polymer are well joined [36]

One significant study explored the impact of thermal boundary conditions in injection molding on the filling flow of PET. The revelations from this research indicated that the application of ceramic mold coatings could notably enhance mold filling capabilities, resulting in a reduction in the pressure requisite for filling the cavity. Remarkably, a maximum cavity pressure decreases of 14%

was observed for the DLC coating at a cavity thickness of 2.5 mm compared to the uncoated setup, elucidating the potential of coatings in optimizing molding processes [37]. In another intricate study, extensive information was amassed from processing domains, morphological structures, and mechanical attributes of specimens through meticulous injection molding simulations, advanced x-ray diffraction techniques, and comprehensive mechanical property assessments. The study employed four distinctive machine learning methodologies to develop predictive models, aiming to forecast the composition of the polymorphic forms (specifically α and β) and the mechanical characteristics of isotactic polypropylene formed via injection molding. This research also focused on delineating the relevance of various processing indicators, providing a holistic view of the interactions and influences within the molding process as shown in Fig.14 [38].

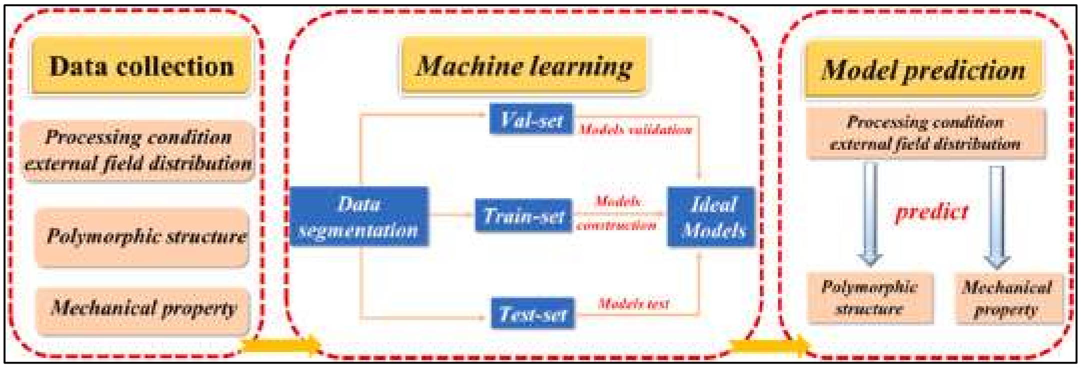


Fig.14. Schematic illustration of the ML procedure flowchart [38]

Moreover, a novel approach was introduced to augment Polypropylene (PP) performance by incorporating anhydride, amine, and specific acrylate monomers through a reactive extrusion process, tailored for water heating applications. The meticulous analysis of the grafting procedure and its subsequent impact on thermal properties revealed a discernible increase in crystallinity and the crystallization temperature. These findings implied that the newly incorporated chains serve a pivotal role in nucleation, offering a novel perspective in enhancing the thermal attributes of polymers as shown in Fig. 15 [39].

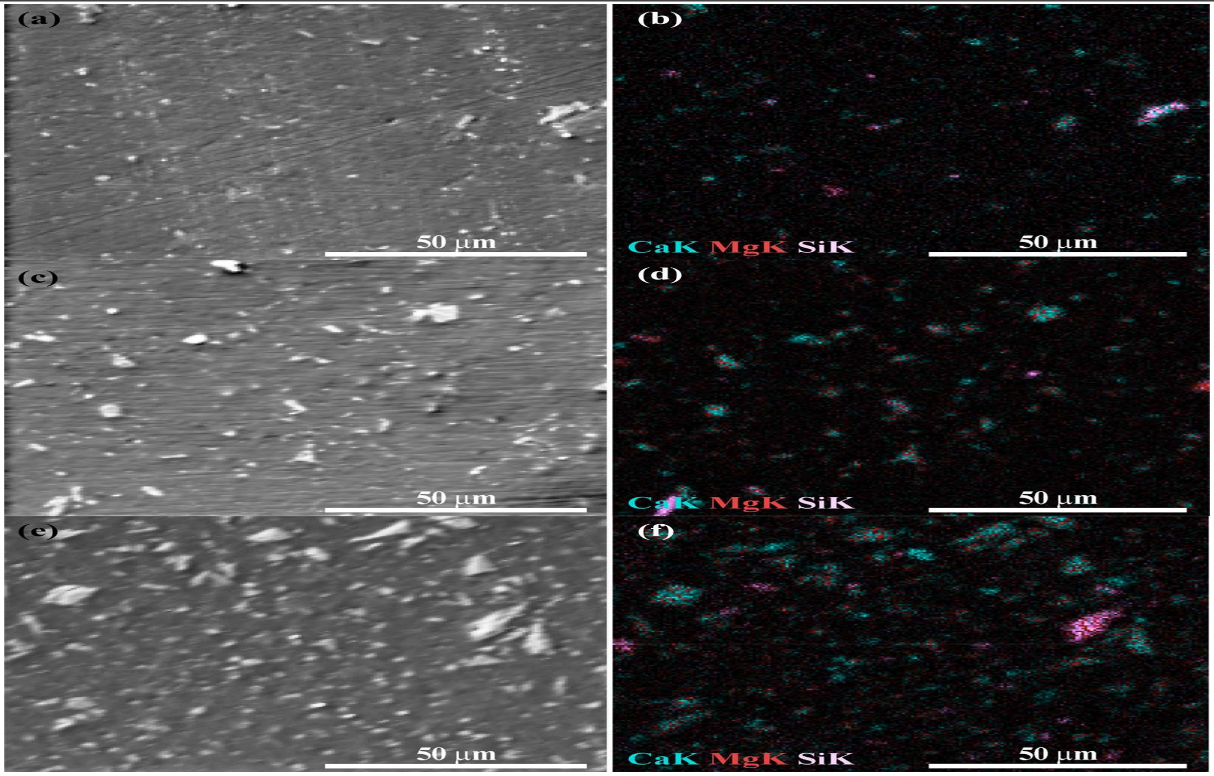


Fig. 15 .SEM-EDS images for samples (a, b) rPET_5MD, (c, d) rPET_10MD, (e, f) rPET_20MD.[39]

In the multidisciplinary field of material science and manufacturing, several studies have brought forth profound insights into the behaviours and capabilities of varied materials under distinctive conditions. A study delving into the mechanical properties of polyamide-6 reinforced with 20% short carbon fibre (PA6-20CF) offered a comprehensive analysis considering varied loading conditions, fibre orientations, strain rates, and specimen thicknesses. The investigative approach encompassed experimental methods, numerical simulations, and SEM image analysis to elucidate the anisotropic elastoplastic behaviour of PA6-20CF. Notably, the bending tests performed on specimens derived from a composite cross member, fabricated by injection molding, revealed significant insights into the material's adaptability and performance [40].

2.3 Material Capabilities and Special Cases

Novel research study focused on the additive manufacturing of cemented carbide, utilizing analogous powder injection molding feedstock. The elucidated findings highlighted the successful fabrication of WC-8%Co cemented carbide through an extrusion-based additive manufacturing process, achieving a remarkable relative density exceeding 99% post a sintering process at 1400°C, showcasing the potential for high-density, high-strength materials in advanced manufacturing applications [41]Moreover, a specialized study aimed at exploring the shape memory capabilities of Shape Memory Thermoplastic Polyurethane (SMPU) employed Differential Scanning Calorimetry to characterize transition temperature and executed thermomechanical tests under diverse strain rates and temperatures. The unearthed results showcased exceptional memory capabilities of SMPU under various conditions, with notable improvements in the shape recovery ratio up to 20% observed with increasing strain rates. However, the influence of escalating strain and temperature levels manifested a decrement in the material's ability to revert to its original form [42]New study, the innovation of sacrificial molds has been highlighted as a pivotal development enabling the fabrication of intricate ceramic parts with undercuts, a feat unattainable with conventional steel molds. The demonstrated feasibility of injection molding using sacrificial molds for fabricating diverse ceramic elements like heating elements and dental implants underscored the versatility and potential of this technique in producing parts with varied electrical conductivities or functionalities as shown in Fig. 16 [43].

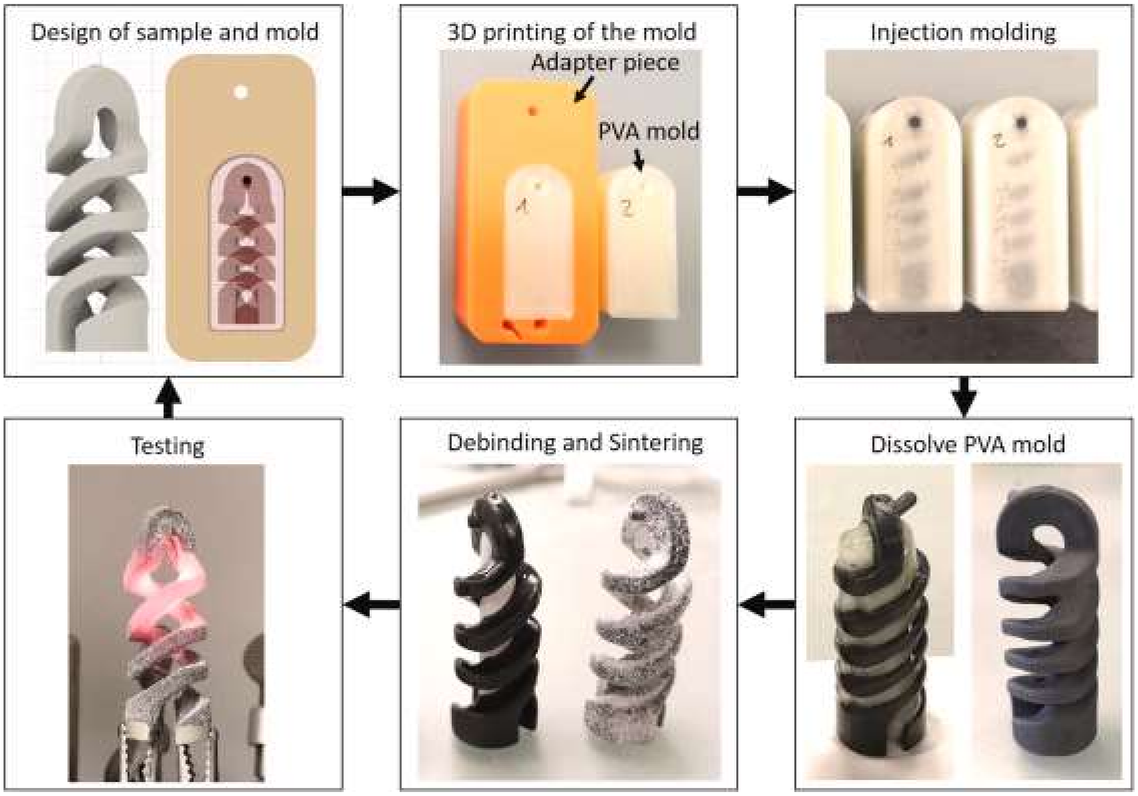


Fig. 16 Overview of the prototyping workflow with sacrificial injection molds for CIM.[43]

In an era marked by rapid technological advancements and multifaceted research pursuits, several innovative studies have pioneered diverse methodologies and insights in material science. A notable study has delved into the realms of direct joining between nano-textured metal and non-crystalline polymer, leveraging heating and cooling injection molding techniques as shown in Fig.17. This study successfully achieved a union between anodized aluminium alloy and PMMA, exhibiting a tensile shear strength exceeding 10 MPa [44].

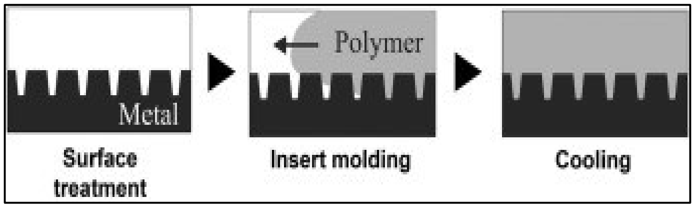


Fig. 17 Schematic diagram of injection molded direct joining (IMDJ) [44]

2.4 Material Innovations and Additives

Research on the fabrication of poly (lactic acid) (PLA)/thermoplastic polyester elastomer (TPEE) blend-based nanocomposites, infused with carbon nanotubes (CNTs), has unveiled remarkable findings. The incorporation of CNTs not only enhanced the crystallizable of PLA but also induced transformative changes in TPEE domains. This led to substantial augmentations in elongation at break and notched impact strength of the blend, witnessing increments up to 290% and 43%, respectively, showcasing the potential for enhanced durability and resilience in composite materials [45]. Additionally, an insightful exploration into the implications of graphene oxide (GO) coating on carbon fibre (CF) surfaces within polyamide 6 (PA6) composites has been undertaken. The results from the study elucidate that the application of GO coating through physical absorption significantly alters PA6's crystal planes, leading to enhancements in tensile and flexural strength and modulus by up to 24% and 25%, respectively. However, this modification also rendered a reduction in impact strength and fatigue life by up to 30% and 23%, respectively, highlighting the consequential trade-offs in material properties [46]. New study, innovative synthesis involving long-chain aliphatic polyester (PE-18,18) in conjunction with long-chain aliphatic poly(H-phosphonate) s (PP) has been explored to augment degradation. The resulting blends exhibited characteristics such as high crystallinity, flexibility, and rigidity, akin to high-density polyethylene (HDPE), and were found to be compatible with techniques like injection molding and 3D printing. The exposure of these blends to diverse solutions led to substantial hydrolytic degradation, manifesting in reduced molar mass and disintegration of the samples as shown in Fig. 18 [47].

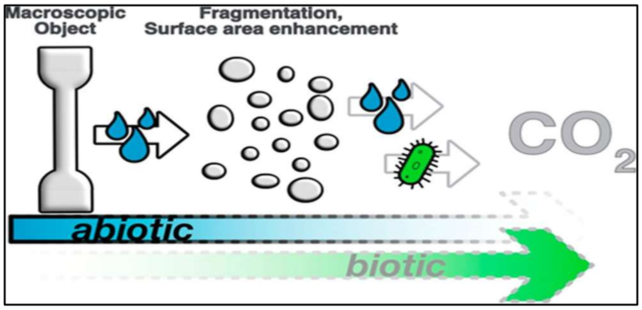


Fig. 18 Observed abiotic degradation resulting in disintegration and surface area enhancement (left) and anticipated further breakdown and eventual mineralization (right) [47]

In advancing the frontier of materials science and engineering, recent research has investigated the versatility and adaptability of different polymers as matrices for zeolite-containing desiccant composites, specifically targeting functional packaging material applications. The exploration involved the creation of composites encompassing up to 50 vol% zeolite, with meticulous analyses conducted on interfacial adhesion through surface characteristic measurement, cyclic loading tests, and evaluations of mechanical property composition-dependence [48]. Moreover, the study discourse on the incorporation of active agents, spanning synthetic and natural antimicrobial agents and antioxidants, in food packaging brings forth insights into their consequential effects on food quality and safety. This discourse extensively reviews the myriad of bulk preparation technologies, including compression molding, injection molding, extrusion molding, blow molding, thermoforming, and electrospinning, elucidating their roles in shaping food packaging products infused with active agents [49]. In the domain of environmental conscientiousness and sustainable design, an innovative study has revealed an improved design paradigm for caps and tools characterized by fewer components, diminished mass, and enhanced production efficiency. Employing the ReCiPe 2016 method across six midpoint impact categories, the study assessed the life cycle phases of tool manufacturing, cap production, and packaging. The insightful results showcased that the refined design yielded over two times lower environmental impacts in the majority of the categories, with the tool manufacturing phase emerging as the predominant contributor to the impacts [50]. In the realm of composite materials and molding processes, recent studies illuminate the intricate relationship between molding parameters and the resultant properties of the materials. One such study meticulously analysed the effects of various molding parameters including packing time, cooling temperature, molding and melting temperatures, packing and injection pressures, and fibreglass percentages. The insights gleaned from this study highlighted the pivotal role these parameters play in affecting warpage and shrinkage in composites. Specific findings indicated that the minimum values for warpage and shrinkage were 0.0051 mm and 2.2886% respectively, with these values being derived from the PC/ABS and PPE/PS composites, thus underscoring the intricate variability inherent in different composite materials[51]. Furthering the exploration into composite properties, another study delved into the impacts of varying shear rates on the properties of polyamide 6/multiwalled carbon nanotube (PA6/CNT) composites, drawing correlations with different processing methods. The findings from this study revealed that the high shear conditions prevalent in injection molding have the potential to compromise the filler network of the composites, subsequently affecting the electrical conductivity. However, an intriguing dichotomy was observed, wherein these high shear conditions also resulted in a more optimal filler distribution, leading to a consequential increase in the tensile strength of the composites as shown in Fig. 19 [52].

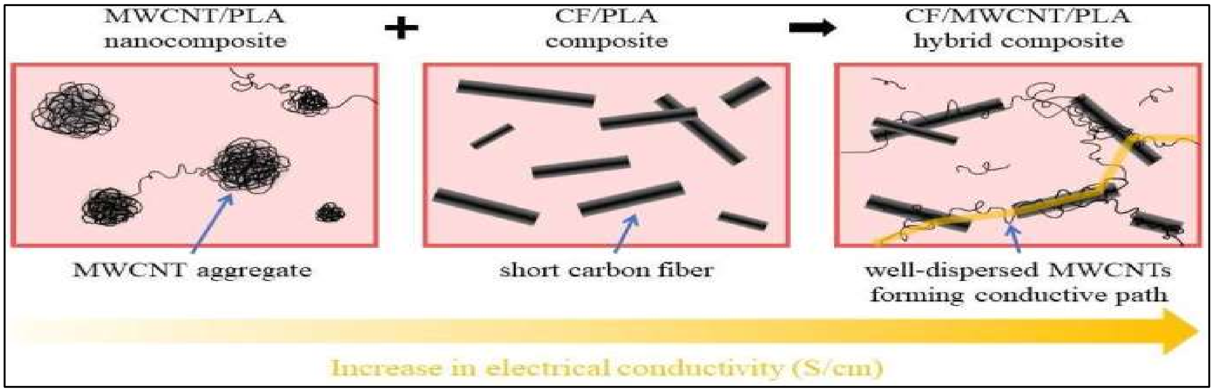


Fig. 19 Schematics of the microstructure of the composites and the forming of conductive paths in the hybrid composites [52]

Advancements in manufacturing technologies have ushered in innovative methods and materials to craft intricate multi-material components. A study elucidated a pioneering method utilizing a granulate-fed 3D printer capable of working with granulated feedstock, diverging from conventional filament-based approaches. The feedstocks are primarily comprised of a commercial ceramic injection molding (CIM) binder amalgamated with various ceramic powders including ZrO2, MoSi2, Al2O3, and feldspar. This research showcased the feasibility of fabricating coloured ZrO2 parts and intricate ceramic high-temperature heating elements, amalgamating electrically conductive and non-conductive components as shown in Fig.20 [53].

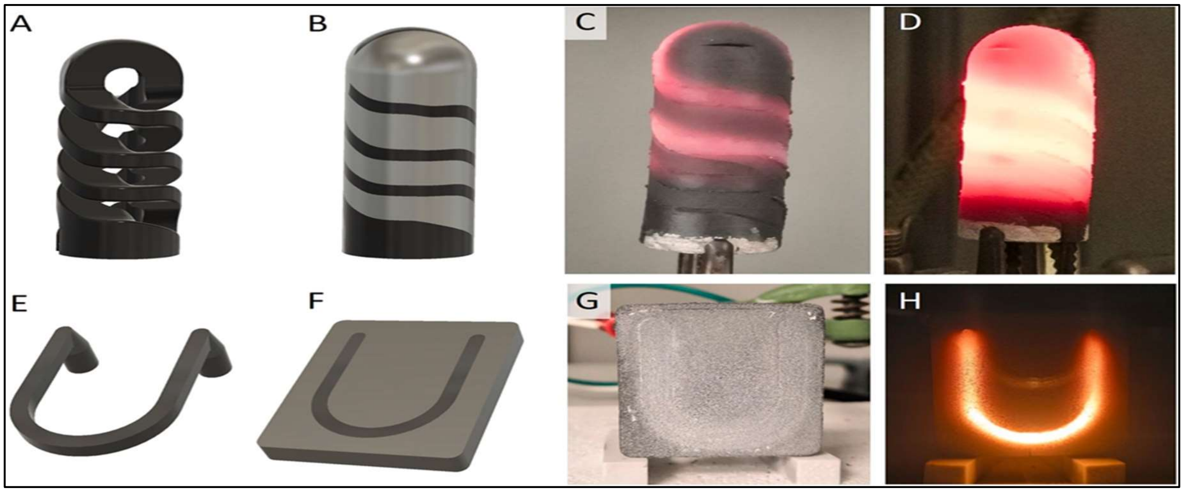


Fig.20 multi-component ceramic heating elements consisting of a MoSi2/Al2O3/feldspar composite. A, E: CAD design of the heating element; B, F: Heating element combined with the supporting structure; C, D, G, H: Sintered parts under operation [53]

In another paradigm, binder jetting, an additive manufacturing technique, has been scrutinized for its proficiency in bonding powder particles with liquid binders' layer-wise. This technique manifests high speed and economic feasibility while processing diverse materials. However, intrinsic challenges pertaining to powder spreading, binder selection, printing quality, post-processing, and scalability exist. Comprehensive review of this technique provided insights into existing technologies, methodologies, and uncovered prospects for future innovations [54]. In the domain of fibre fabrication, the study elucidated the development of PHBHHx fibres using the novel centrifugal fibre spinning (CFS) technique, offering meticulous control over fibre morphology and properties. It was found that elevated polymer concentrations yielded fibres of superior thickness and strength. These fibres could be annealed into compact top layers, proving their potential in applications such as food packaging or as active substrates. This research conducted a comparative analysis between PHBHHx fibres and other prevalent bioplastics and fibre spinning methodologies [55]. A novel study introduced a method to construct hybrid structures by amalgamating polymers with galvanized high-strength steel (GHSS), exploiting injection molding coupled with a hot water treatment (HWT) procedure. The HWT methodology facilitated the creation of nanoscale needle-like structures on the zinc coating, enhancing the joining strength between the metal and polymer interfaces. This research meticulously evaluated the influence of HWT parameters on surface finish and the overall integrity of the formed bond, marking a pivotal step in the synthesis of multi-material composites [36].

2.5 Applications and Environmental Considerations

The progressive advancements in material science and simulation methodologies have steered pivotal research endeavours to enhance the resilience and sustainability of various materials and structures. One such innovation is depicted by a novel co-simulation technique, meticulously designed to predict the impact resistance of composite wheels, assimilating the true essence of tire structures and material nuances. The validity of this approach is substantiated through a precise 13-degree impact analysis, revealing a noteworthy convergence between simulated projections and actual experimental data, thereby highlighting the profound influence of disparate tire designs and mesh models on a composite wheel's impact endurance as shown in Fig. 21 [27].

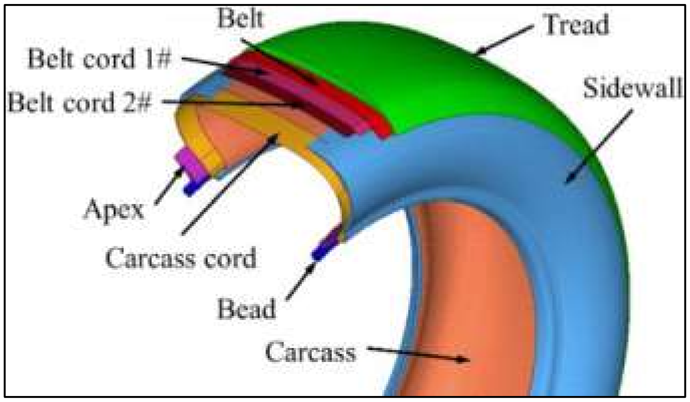


Fig. 21 Finite element model of the composite tire [27]

In another domain, extensive research on Mater-Bi, a bio-based and biodegradable polymer, exemplifies its potential as an environmentally viable alternative to fossil-derived polymers like polypropylene, specifically in fabricating trays for marine aquaculture. The comparative analysis underscores the superior environmental benefits of employing Mater-Bi, considering its inherent properties and biodegradation rate [56]. An analytical study juxtaposed phase-changing materials (PCM) against conventional insulation in the architectural realm of non-residential edifices situated in torrid climates. Employing intricate simulations and economic evaluations, the investigation explored the thermodynamic, economic, and environmental ramifications of diversely configured walls, incorporating PCM and brick layers. Findings from this study accentuate PCM's capability to diminish cooling load, air-conditioning dimensions, floor area, and energy expenditure, with the optimal selection of PCM type and thickness being contingent on the thickness of the brick layer and the prevailing climate [57]Another insightful research endeavour concentrated on the waste management aspects post-injection process, particularly focusing on the manufacturing of polyamide products predicated on regranulate. It was discerned that the integration of up to 15 wt.% of regrind with virgin polyamide doesn't compromise its intrinsic characteristics like impact and tensile strength, and hardness. The investigation also delved into analysing the structural composition of glass fibres in pure granulate and in granulate derived from milled runner waste, providing a deeper understanding of the material properties [58].New study, a thorough exploration of the evolution of woven natural fibre polymer composites, utilizing various polymer matrices and natural fibres such as jute, flax, kenaf, hemp, and bamboo, has been compiled. This compilation renders a quantitative insight into the mechanical, thermal, and viscoelastic attributes of these composites, alongside their fracture toughness, impact resistance, and ballistic performance, encapsulating the extensive research efforts in this field [59].

3. Process

In this section, we delve into the intricate domain of processes associated with material science, elucidating on methodologies and technologies pivotal for optimizing material manipulation and ensuring quality control. The discourse encompasses an in-depth examination of various optimization algorithms and methodologies, as well as the integration of real-time sensing and monitoring technologies. These components collectively play a crucial role in enhancing the efficiency, reliability, and overall quality of material processing.

3.1 Process Optimization and Quality Control

Advancements in research methodologies and analytical techniques continue to enhance our understanding and optimization of various processes and applications. In one innovative approach, authors have introduced a method that significantly outperforms conventional probe-type sensors in measuring temperature. Validated across a temperature range of 200°C–360°C, this novel technique achieves a remarkable error margin of less than 1.6%. Further application of this method has enabled the visualization of the filling behaviour of conventional PPS and high-thermal-conductivity PPS, revealing critical insights into their differences in flow front, cooling rate, and ductility [60]Simultaneously, the exploration of the effects of various input factors such as molding temperature, cooling time, and injection pressure on the tensile strength of molded components has been undertaken. Utilizing robust analytical approaches like Taguchi optimization, regression models, and variance analysis, researchers optimized and analysed process parameters. The study concluded that optimal tensile strength is realized at a molding temperature of 70°C, a cooling time of 60 s, and an injection pressure of 90 MPa [61]Additionally, another detailed study underscores the impact of specific molding variables including packing duration, cooling degree, molding and melt temperatures, and packing and injection pressures, along with fibreglass content, on warpage and shrinkage levels. The research determined that the minimum values of warpage (0.0051 mm) and shrinkage (2.2886%) were associated with PC/ABS and PPE/PS composite materials, respectively [62]. Moreover, a novel two-stage method has been developed, consisting of a text-to-image synthesis stage and an image refinement stage. This method, designed to generate low-resolution images from text captions and subsequently refine the image quality and diversity, has been evaluated on multiple datasets including CUB, COCO, and Oxford-102. The outcomes of the evaluations indicated that the new method surpasses existing ones in aspects such as visual quality, diversity, and alignment with the text [63]. In the exploration of refining injection molded parts, significant efforts have been directed towards minimizing common defects such as weld-line width and sink-marks depth. A notable study employed a multifaceted approach, leveraging the hybrid methodology of the Taguchi-WASPAS method coupled with the Ant Lion optimization algorithm. This meticulous approach, taking into account eight influential factors including melting temperature, mould temperature, cooling time, injection pressure, back pressure, holding pressure, ambient temperature, and holding time, has yielded optimal factor settings, shedding light on nuanced defect minimization strategies [64]. Concurrently, innovative research has been conducted to infuse graphene and ferro ferric oxide nanoparticles into a polypropylene matrix, acting as photothermal magnetic fillers. Authors have utilized a numerical model to scrutinize the directed migration of these advanced fillers under the influence of an external magnetic field. The demonstrable outcomes of this integration are noteworthy, revealing surfaces with augmented light absorption, photothermal conversion, and substantial reductions in ice adhesion under the impact of solar irradiation [65]. Moreover, significant insights have been drawn regarding the morphology and mechanical properties of 3D-printed polypropylene components, crafted through fused filament fabrication (FFF). It has been discerned that the contact geometry profoundly impacts local deformation during deposition, thereby influencing the resultant morphology and mechanical properties, especially when the contact temperature is beneath the material's melting temperature. Furthermore, elevating the contact temperature above the melting point renders the morphology more homogeneous and enhances the strength properties of the components [66]. Additionally, an in-depth analysis on powder characteristics in Low-Pressure Injection Molding (LPIM) applications has been conducted, concluding that the finest powder, measuring below 10 µm, presented exemplary molding performance and sintered properties. This included achieving a relative density of approximately 90%, an ultimate tensile strength of around 225 MPa, and an elongation at break of about 24%. The study also advocated that irregular iron powders hold promising potential as viable alternatives to spherical powders in LPIM applications, emphasizing the influence of powder characteristics and sintering parameters on the ultimate quality of the final product [67].

3.2 Methodologies and Algorithms for Optimization

The development and analysis of equations pertaining to heat transfer from polymer melts in injection moulds have been pivotal in enhancing the understanding of molding processes. A novel equation, substantiated through rigorous analysis, was compared with existing models utilizing common plastics like ABS, PC, and PP. This equation, which harmonizes well with pre-existing literature, posits the notion that employing an average temperature across the moulded part’s cross-section as the ejection temperature is more pragmatic than relying on the mid-plane temperature [68]. Simultaneously, an optimization study on marble dust-filled polymer composites was conducted, employing a robust decision-making technique. The evaluation was focused on PLA and rPET composites with varying marble dust contents, assessing diverse properties. The optimal outcome emerged as the 10 wt% marble dust-filled PLA composite, its efficacy corroborated through various validation methods [13]. The study exploring material jetting technology elucidated its potential in fabricating resin inserts for micro injection molding. The examination of the benefits and critical aspects revealed the technology's proficiency for prototyping but emphasized the necessity for a balance between cavity geometry and the production method of the insert [69]. The exploration of Big Area Additive Manufacturing (BAAM) printers in the field of material science has marked a significant advancement, particularly in the fabrication of bonded permanent magnets. The research focused on the capabilities of BAAM printers to achieve a magnet loading fraction exceeding 0.65, a milestone that distinctly surpasses the conventional limitations inherent to injection molding methodologies [70]. In the realm of material science and manufacturing, several studies have delved into the optimization and innovation of various processes. A significant research study on waste management post-injection process focused on the manufacturing of polyamide products leveraging regranulate. The study's findings illustrated that the incorporation of up to 15 wt.% of regrind to virgin polyamide did not compromise its fundamental properties such as impact strength, tensile strength, and hardness. The research provided insights into the structural intricacies of glass fibres in both pure granulate and that derived from milled runner waste [60]. Additionally, extensive research has been conducted on the impact of various parameters such as powder loading, binder composition, and sintering conditions on the porosity and mechanical properties of sintered compacts. The outcomes of these studies revealed that the porosity and bending strength of the compacts could be meticulously controlled and optimized by manipulating these parameters, thereby rendering the sintered compacts as viable materials for artificial bone applications [71]. In another innovative approach, the integration of laser powder bed fusion (LPBF) with vacuum infiltration (VI) was employed for the preparation of silica-based ceramic cores, which were reinforced with ZrSiO4. This research aimed to produce cores intended for hollow blade production. The pre-sintering of these cores at 1100°C notably enhanced the mechanical properties, achieving a room-temperature flexural strength of 17.21 MPa and a high-temperature flexural strength of 13.90 MPa with the ZrSiO4 addition at 10 wt.% [72]Furthermore, Powder Injection Molding (PIM) has been highlighted as a pivotal method capable of manufacturing tungsten parts with remarkable near-net-shape precision and cost-effectiveness. This method encompasses key steps such as feedstock development, design and simulation of new PIM tools, injection molding, debinding, and heat-treatment [73].

3.3 Real time Sensing and Monitoring Technologies

Advancements in real-time process monitoring in plastics manufacturing are underscored by a study that introduced a multivariate shrinkage sensor (MVSS) design, aiming to enhance the prediction of molded part quality. The novel design, when tested with high-impact polystyrene (HIPS) and polypropylene (PP), demonstrated remarkable accuracy, with the MVSS data yielding a prediction error of a mere 0.11%, showcasing a significant reduction in error compared to conventional methods [74]. Research in measuring devices has led to the development of an annular measuring device, TRAC, equipped with thermocouples and pressure sensors, designed to monitor variations in temperature and pressure induced by viscous dissipation in the flow. An inverse method anchored in the power law model was developed to derive viscosity from temperature measurements, tested on polymers like PP and PS, and subsequently compared to existing viscosity curves from literature and a rheometric nozzle, offering a nuanced understanding of viscosity variations [75]. Additionally, a meticulous analysis of machine process data was executed to develop an automated method capable of evaluating start-up behaviour and machine behaviour post alterations in machine parameters. Employing dynamic time warping correspondences (DTW), the research investigated process behaviour using high-resolution data, focusing on elements such as injection pressure, flow rate, and screw volume, illuminating the intricate behaviours and alterations during the process [76]. The exploration of computational models revealed insights into their respective advantages and disadvantages, particularly focusing on computational cost and accuracy. It was reported that the maximum differences in time efficiency for the GHS and GNF approximations were 8.9% and 3.4% respectively, presenting an elaborate perspective on the efficacy and precision of different computational models in scientific applications [77]. In the pursuit of optimizing injection molding processes, several studies have used advanced methodologies to assess and enhance the effectiveness of various techniques. One study utilized both numerical simulation and molding experiments to assess the effectiveness of the D-IMD/MIM process. This process was reported to facilitate a more balanced and homogeneous temperature and cellular distribution. Impressively, it was found to reduce warpage deformation by a substantial 71.68%, compared to the S-IMD/MIM process, demonstrating the enhanced capability of the proposed method in maintaining structural integrity [78]. Additionally, another research work employed Moldflow analysis to delve deep into the causes of sidewall deformation and to optimize the positioning and type of sensors strategically. Following the analysis, small-batch production experiments were conducted to affirm the feasibility and accuracy of the developed monitoring system. This study shows that the proposed monitoring method is pivotal in efficiently overseeing product quality and, notably, in curtailing development costs, highlighting its practicality in real-world manufacturing scenarios [79]. Exploration into the realm of high-temperature resins for additive manufacturing has yielded significant results, especially in the context of producing inserts for micro injection moulding (µIM) for prototyping and small batches. It was revealed that the utilization of resin inserts exhibited isolating behaviour, mitigating thermal dissipation and maintaining lower viscosity even during the application of packing pressure. This research, through an empirical campaign using both steel and high-temperature resistance resin inserts, validated the significant findings and underscored the potential of high-temperature resins in enhancing the efficiency and effectiveness of µIM processes [80]. In the evolving landscape of injection molding, several studies have provided crucial insights into the optimization and application of various technologies and materials. A research study focused on the utilization of material jetting technology to fabricate resin inserts specifically for micro injection molding. This exploration discerned the notable advantages and inherent challenges pertinent to the industrial incorporation of these inserts. While the inserts exhibited significant utility in prototyping within micro injection molding, it was evident that a balanced compromise is imperative between the cavity geometry and the production methodology of the insert.[69]. A detailed study delved into the nuances of employing optical liquid silicone in injection molding tailored for automotive components. Leveraging advanced simulation software and strategically placed sensors, the authors were able to optimize melt temperature and V/P switching points. The enhancements in process parameters illuminated the pathway to heightened transmittance, diminished volume shrinkage, and reduced residual stress, all while contributing to a decrease in carbon emissions, underscoring the environmental implications of optimized process parameters [81]. In another innovative study, the intricacies of cell deformation in PP/PTFE foams, prepared through foam injection molding (FIM) with supercritical nitrogen as a foaming agent, were investigated. It was observed that augmenting the contents of nitrogen and PTFE positively influenced the deformation of the cells, with deformation surprisingly occurring alongside larger cell density. By viewing cells as the dispersed phase, this research not only offered a novel perspective on studying cell deformation in FIM but also enriched the understanding, paving the way for future endeavours in preparing foams with oriented cells [82].

4. Cooling

In this critical examination, the focus is narrowed down to the realm of cooling, with a specific spotlight on the innovative design, manufacturing techniques, and performance optimization of conformal cooling channels. These channels represent a significant advancement in thermal management, offering enhanced cooling efficiency and uniform temperature distribution compared to traditional cooling methods. Through a meticulous exploration of their design principles, manufacturing processes, and performance metrics, this section aims to unravel the nuances of conformal cooling channels and their pivotal role in optimizing material processing. The discourse endeavours to provide a comprehensive understanding, paving the way for further innovations and efficiency improvements in thermal management practices.

4.1 Conformal Cooling Channel Design

Recent developments in additive manufacturing have dramatically transformed the process of injection molding, particularly with the invention of conformal cooling channels (CCCs). Studies have been conducted to formulate a structured, module-based method for creating these channels within the tools used in injection molding, utilizing the capabilities of solid freeform fabrication technologies. This novel approach has been evidenced to enhance both production rate and part quality [83].

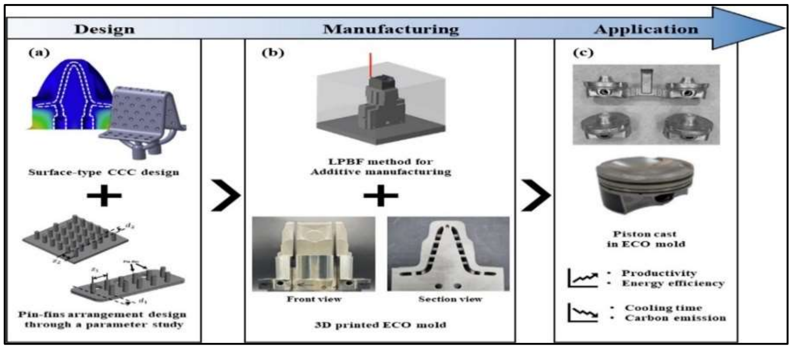


Fig. 22. Illustrating the design concept and additive manufacturing of the ECO mold with the CCC, contrasted with the conventional mold with a simple straight cooling channel. [84]

Recent advancements in additive manufacturing, particularly the laser powder bed fusion method, have enabled the development of eco-friendly molds with three-dimensional cooling channels, as illustrated in Fig. 22. These channels have been shown to reduce casting process times by 21% [84]. The application of computer-aided engineering (CAE) simulations for designing conformal cooling channels (CCCs) in injection molding has led to notable enhancements. Various techniques including the radial basis function network, response surface methodology, genetic algorithms, and glow worm swarm optimization have been successfully utilized, producing superior outcomes [85].

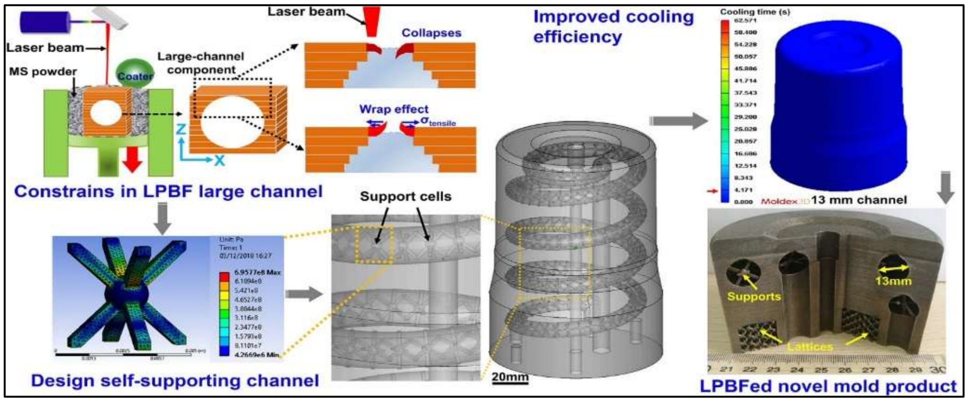


Fig. 23 Depiction of a novel injection mold featuring a large self-supporting cooling channel and tailored porous structures [86]

A design has been processed for a conformal cooling injection mold, leveraging laser powder bed fusion (LPBF) to boost cooling efficiency and enhance manufacturing output, as depicted in Fig. 23. The findings revealed that the self-sustaining channel amplified cooling efficiency by cutting down the cooling time by over 20% when compared to an 8mm-channel injection mold [86]. A unique scaffold design has been introduced for conformal cooling, aimed at delivering a more evenly cooled surface in injection molding. The simulated outcomes demonstrate that the scaffold cooling method provides a more even heat distribution with a decreased incidence of in-cavity residual stress compared to traditional techniques. This mitigates injection mold flaws such as thermal stress or warping, thereby increasing productivity [87].

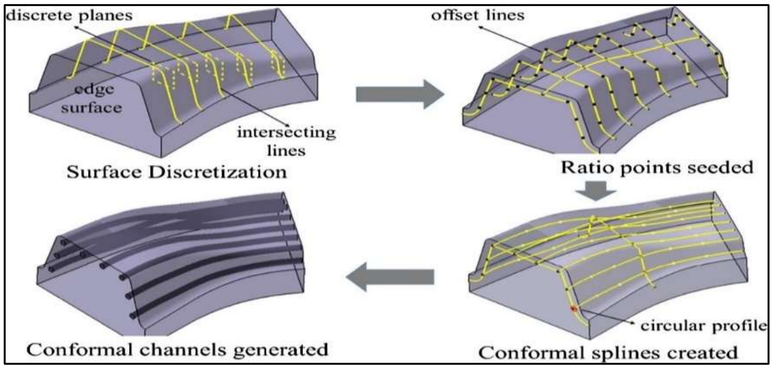


Fig. 24 Process for designing Longitudinal CCC [88].

An innovative design for longitudinal conformal cooling channels (CCC) has been proposed for a B-pillar tool. This optimization yields a Pareto-optimal frontier that comprises the best combinations of design parameters. In addition, a unique manufacturing technique for hot stamping tools featuring longitudinal CCC has been presented, as illustrated in Fig. 24 [88].

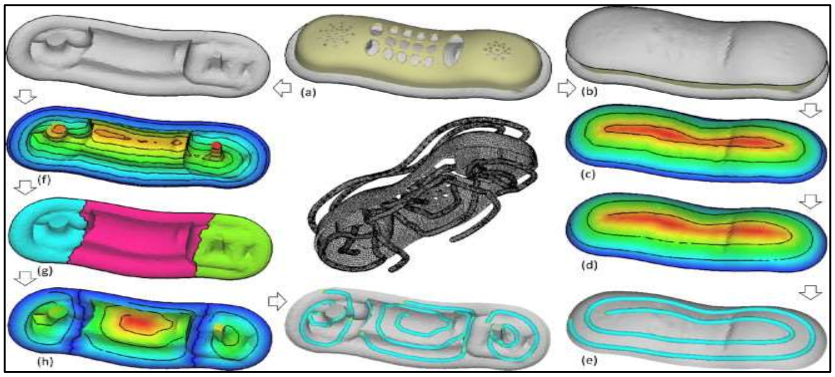


Fig. 24 Illustration of the process for creating spiral and conformal cooling channels in the upper mold (right column) and the lower mold (left column) [89]

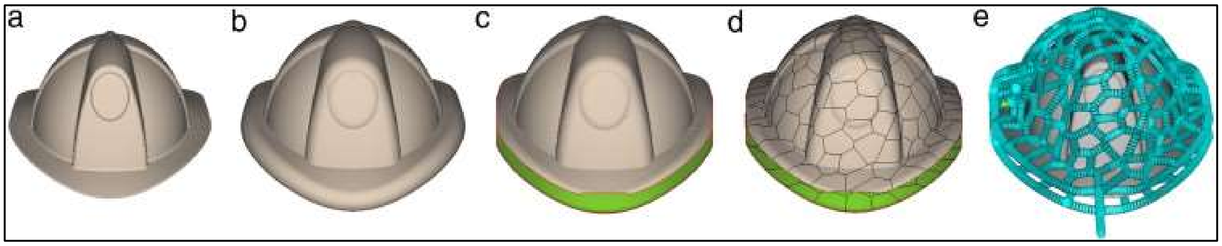
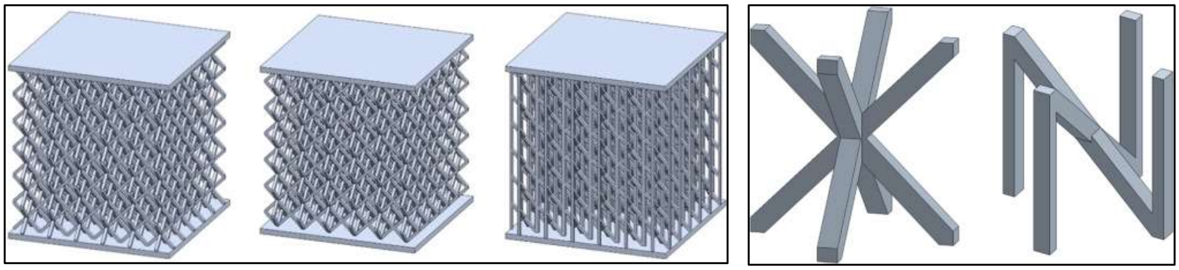


Fig. 25. Stages of the cooling circuit generation algorithm: (a) a given model for rapid tooling fabrication, (b) the offset surface of the given model, (c) the separate offset surface acting as the conformal surface, (d) the refined discrete CVD, and (e) the final conformal cooling circuit [90]

A novel approach for automatic designing of conformal cooling circuits for injection molding has been unveiled, as depicted in Fig.25. Simulation outcomes indicate that these cooling circuits, created using this method, are highly effective in minimizing cooling time and maintaining a uniform temperature and volumetric shrinkage, consequently enhancing the production speed and quality of the parts [90]. U-shape milled groove conformal cooling channels, leveraging a combination of analytical methods and 3D CAE simulations to optimize channel configurations and achieve uniform cooling, reduced cooling time, and elevated molded part quality. A case study validates the efficiency of this approach, highlighting its capability to fine-tune optimization results quickly and reduce the effort required by designers [91]. The research underlines the ability of CC channels to decrease cycle time by as much as 70% and notably improve shape deviations. Various design methods, channel configurations, and production techniques are evaluated, with epoxy casting and laser powder bed fusion (L-PBF) being the most suitable for certain mold materials [92]. The advantages of conformal cooling channels have also been extensively studied within the Rapid Heat Cycle Molding (RHCM) framework. Although the potential of CCCs in RHCM is yet to be fully explored, it's recommended that future research focuses on these channels to achieve improved thermal uniformity and shorter cycle times [93]. In the pursuit of enhancing cooling efficiency, a novel visibility-based cooling channel generation methodology has been proposed. Drawing an analogy between the cooling process and visibility, this method culminates in a superior cooling channel design, diminishing the number of design modifications and enhancing cooling performance. It has been concluded that such a methodology can help mitigate injection mold defect formations and boost productivity [94]. Furthermore, research has showcased a smart injection mold for an automotive part with spiral conformal cooling channels made using selective laser melting (SLM), which led to a 30% reduction in cycle time and improved quality control through sensor systems [95].



[a] [b]

Fig. 26 (a) CAD visuals of cross, diamond, and N cell lattices with 1 mm shims. (b) Unit cells: cross (left) and N (right) [96]

The idea of conformal cooling layers has been presented, filled with self-sustaining, recurring unit cells that form a lattice within the cooling layers. As illustrated in Fig.26, this results in higher heat transfer rates and a decrease in variations of tooling temperatures. A case study revealed that these conformal layers reduce cooling time by 26.34% compared to traditional cooling channels [96]. The injection molding sector is leveraging three-dimensional printing and laser sintering to create conformal cooling channels, achieving up to a 50% reduction in cooling time and enhanced mold temperature control, thereby optimizing traditionally challenging cooling system designs and contributing to substantial cost savings and quality improvement [97]. In the ongoing pursuit of cooling efficiency, studies have in on unique designs like Milled Grooved Square Shape (MGSS) conformal cooling channels. These channels have demonstrated an improvement in cooling uniformity and a reduction in cooling time by 65%, as well as a reduction in warpage by 14-54% compared to straight-drilled cooling channels. This provides a more cost-efficient and effective alternative for enhancing the quality and productivity of molded parts [98]. Introducing Milled Grooved Square Shape (MGSS) conformal cooling channels in injection molding processes, this article demonstrates their superior efficiency and surface area, yielding a 12 to 50% improvement in thermal distribution and a 6 to 8% reduction in cooling time compared to conventional channels. The ease of designing, fabricating, and assembling these channels on hard tooling is highlighted, emphasizing their substantial potential in molding industries [99]. This study introduces a new lattice element for injection mold cooling systems, employing parameterized geometric design and optimization algorithms to enhance thermal exchange efficiency, especially in complex parts, and ensure structural safety during injection processes. Validated through simulations, this conformal system simplifies design, reduces manufacturing cycle time, and improves part quality without the need for expert dimensioning [100]. A hybrid cooling model that merges fluted conformal cooling channels and Fast cool inserts for industrial parts with intricate geometries. This results in a reduction in cycle time by 27.442% and an enhancement in thermal exchange by 4334.9% [101]. A structured, module-based method for designing conformal cooling channels has been proposed, splitting the tool into geometric regions and implementing six criteria as constraints for successful designs. Facilitated by solid freeform fabrication processes like 3D printing, this method leads to increased production rates and better quality in injection molding tooling [102]. The characteristics of conformal cooling systems used in molds for injection molding processes have been examined. While conformal cooling systems can help maintain consistent part quality and minimize cooling times, the paper concludes that the improvements may be negligible for plastic parts with lower complexity [103]. Another novel idea is the variable distance conformal cooling channel (VDCCC) design, which compensates for the gradual increase of coolant temperature, allowing for more effective heat removal. Results show that the VDCCC design surpasses conventional CCC designs, with lower maximum part temperature, cooling time, and volumetric shrinkage, thereby reducing the injection molding cycle time [104]. Adding to the pool of novel designs, a thermally controlled extrusion insert with conformal cooling channels has been proposed. This inserts design, manufacturable through SLM technology, has the potential to double the production rate without reaching critical temperature ranges, ensuring defect-free profiles and extended insert lifetime [105]. The research shows that conformal cooling channels, situated closer to the die surface, offer more efficient cooling, reaching an efficiency of 54.83% after 5 sec. of simulation. This results in a more even temperature spread across the mold insert when compared to traditional cooling channels [106]. In the wider scope of molding, the examination of epoxy-based rapid molds featuring profiled conformal cooling channels has been initiated. These channels have demonstrated superior cooling performance in comparison to their circular equivalents. The application of an empirical material formulation with 41 vol.% Cu powder has achieved 88% of the cooling performance of commercial materials while lowering material costs to 60% [107]. The innovative variable radius conformal cooling channel (VRCCC) design, when combined with solid freeform fabrication technologies, has displayed better cooling performance and superior part quality. [108]. A novel concept of a conformal cooling layout for non-pneumatic tires forming molds has been proposed. A semi-annular conformal cooling channel scheme was determined to have the most effective cooling impact, reducing the cooling loop pressure loss by 77%, cutting down the cycle time and cooling time by 9.6%, and lowering the tire volume shrinkage rate by 0.012% [109]. Studies have also delved into alternative sealing methods for conformal channels in layered tools utilized in thermoforming and composites forming. High-temperature adhesives manually applied around conformal holes between each layer were found to provide the best combination of sealing and thermal performance [110]. The automated design method for honeycomb conformal cooling channels in cold runner systems has shown potential in enhancing part quality and consistency, reducing shrinkage, and minimizing warpage for parts produced from the same two-cavity mold [111]. One study shows the effects of introducing sub-grooves to a square-shaped cooling channel to boost cooling performance. The optimal sub-groove design led to a 24.3% reduction in ejection time by increasing coolant velocity and the heat transfer rate from molten plastic to coolant [112]. UG and Moldflow software to develop and assess heat transfer models for conformal and straight pipe cooling systems, revealing that conformal systems provide a more homogeneous temperature distribution, improving molding quality and efficiency for plastic parts. The optimization of these superior conformal cooling systems was subsequently achieved using orthogonal tests and range analysis methods [113]. Study introduces a new design approach for conformal cooling channels using series and parallel patterns. It demonstrates that thoughtful design can augment cooling performance and overall benefits in the injection molding process [114]. A cost-efficient method for fabricating a wax injection mold with different cross-sectional cooling channels has been suggested. The method achieved an 81% reduction in cooling time when compared to a mold without cooling channels [115]. Different geometrical configurations of these channels have shown distinct impacts on thermoforming mold performance, with serpentine geometry leading to better cooling performance and a higher cooling curve slope compared to traditional shapes [116].

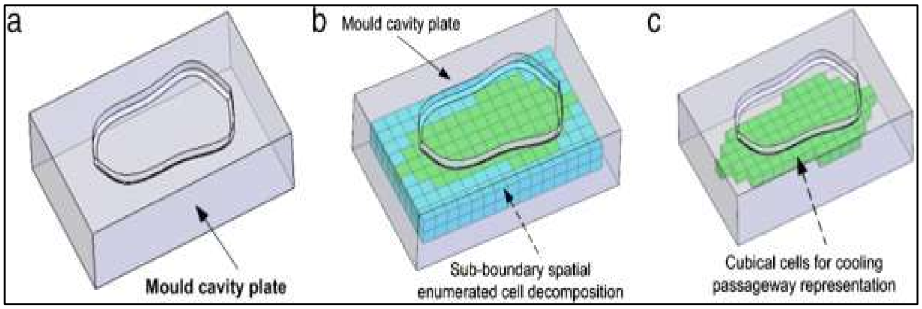


Fig. 27 (a) Mould cavity plate, (b) sub-boundary spatial enumerated cell decomposition within mould cavity plate, and (c) cubic cells for cooling passageway representation [117]

An innovative design approach for a conformal cooling passage with multi-connected porous features, based on the principle of duality. The objective of this method was to deliver a more uniform cooling performance and prevent injection mold flaws such as warpage or hot spots as shown in Fig.27 [117].

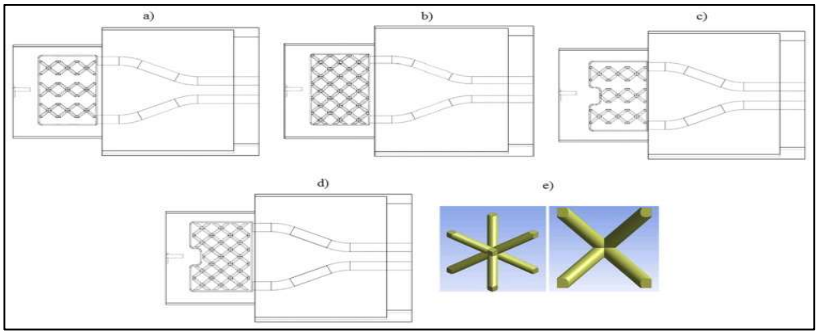
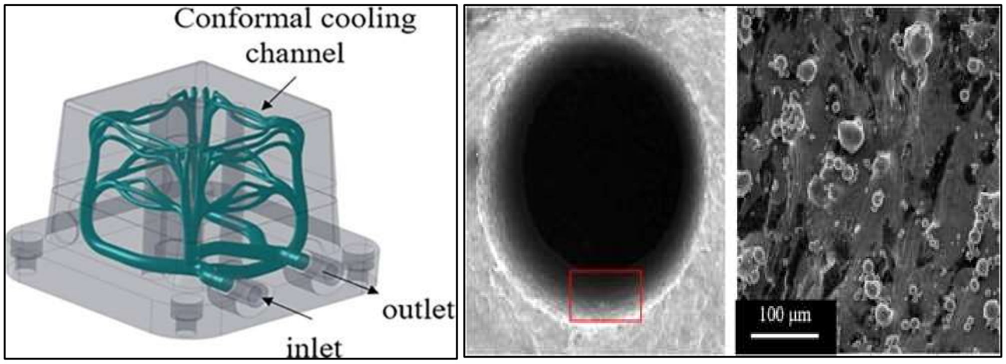


Fig. 28 (a) CCCv model 1; (b) CCCv model 2; (c) CCCv model 3; (d) CCCv model 4; and (e) BCC lattice structure [118]

A particular study delved into the thermal and mechanical behaviour of four distinct lattice-supported conformal cooling cavity configurations for injection molds. The findings highlighted that these novel cavity designs significantly reduced the cooling time by approximately 68.5% to 74.2%, in comparison to the conventional straight-drilled geometries as shown in Fig.28 [118]. The advancements in conformal cooling technology have brought about significant improvements in the quality and efficiency of injection molding processes, and ongoing research continues to explore new possibilities in this exciting field. The emerging technologies, such as additive manufacturing methods and intelligent design algorithms, are revolutionizing the way we approach the design and creation of these channels. These advancements, as demonstrated in various studies, have resulted in significant reductions in cycle time, improved uniformity of cooling, and enhanced part quality, among other benefits.

4.2 Conformal Cooling Channel Manufacturing Techniques

This study explores the efficacy of profiled conformal cooling channels (PCCC) in injection molding, contrasting it with circular conformal cooling channels (CCCC) by employing two maraging steel injection molding tools, designed and created through direct metal printing technology. The investigation, conducted using Moldex3D simulation software, revealed that PCCCs are superior, reducing cooling time by approximately 33.33% compared to CCCC, with optimal coolant water temperature noted at 26°C for dimensional accuracy and energy efficiency[119]. This review illuminates the pivotal role of direct rapid manufacturing in creating molds with conformal cooling channels (CCCs), potentially standardizing its use for enhanced productivity and quality across various manufacturing processes[120]. The manufacturing of these CCCs has been facilitated by emerging technologies such as additive manufacturing and rapid prototyping. the transformative role of rapid prototyping assisted conformal cooling channels in manufacturing, suggesting its potential to become a standard, replacing conventional methods for intricate structures and improving overall quality and productivity [121].A significant advantage of CCCs is their potential for improving heat dissipation, thereby reducing cooling and cycle times. For instance, the utilization of triply periodic minimal surface (TPMS) structures in CCCs has been shown to decrease cooling time by up to 40% [122]. This study demonstrates the effectiveness of using selective laser melting (SLM) to create parts of pressure mold cooling systems with enhanced heat dissipation properties. lowered the average temperature of the sprue spreader in the cooling channel zone by approximately 20°C [123]. HLM creates cost-effective bimetallic injection molds with better joint strength, outperforming conventional CNC manufacturing, and integrates conformal cooling channels for enhanced performance [124]. Meanwhile, the application of selective laser melting (SLM) in manufacturing plastic molds with complex CCCs has resulted in a 30% increase in cooling efficiency [125]. In fact, one study using SLM demonstrated a reduction in cooling and cycle times of 19-20% and a reduction in part dimensional shrinkages of 13.5-16.7% [126]. A revolutionary conformal cooling channel design and a hybrid manufacturing method, merging machining and metal powder additive manufacturing, which results in significantly reduced warpage and a 36% reduction in molding cycle time compared to conventional molds. The innovative approach also achieves a 53% and 60% reduction in manufacturing costs and time respectively, highlighting the substantial benefits of this combined methodology in optimizing injection mold production [127]. Hybrid layered manufacturing using metal inert gas (MIG) cladding and CNC milling has been employed to manufacture H13 tool steel injection molds with CCCs, resulting in improved cooling performance and a hardness of 53 HRC for the deposited material [128] Electron Beam Melting (EBM) process for optimizing rapid tooling in injection molding, focusing on enhancing cooling systems critical to part cycle time through extensive heat transfer simulations and experimentation. The research provides pivotal design guidelines and demonstrates the potential of EBM technology in significantly reducing cycle and product development time in the mass production of diverse and intricate plastic parts. [129]. Laser Powder Bed Fusion (L-PBF) in additive manufacturing to integrate dynamic conformal cooling channels close to the mold surface, optimizing the visual quality of injection-molded components through advanced thermal simulation and experimental testing with maraging steel (1.2709). The developed hybrid tools and the subsequent enhancements in the molding process demonstrate significant advancements in achieving superior temperature modulation and component surface appearance [130]. This study thoroughly assesses the efficacy of using additively manufactured conformal cooling inserts in plastic injection steel molds, indicating a marked reduction in global scrap rates, including a 7.05% decrease in average appearance and a 7.35% decrease in variability. The detailed analysis, utilizing historical production data and distribution functions, demonstrates the substantial improvements in production efficiency and reductions in defects, emphasizing the transformative potential of this technology in plastic injection processes [131].



[a] [b]

Fig. 29 (a) A mold featuring a conformal cooling channel (Image courtesy of IPC). (b) SLM vertically assembled maraging steel 300 channel (ø3) and its surface texture [132].

This research delves into the efficacy of abrasive flow machining (AFM) in mitigating surface roughness in intricate cooling channels crafted using selective laser melting (SLM). The findings indicate that AFM is successful in enhancing surface smoothness in all examined conformal cooling channels. For example, a straight conformal cooling channel improved from a surface roughness of 7.6 µm Sa to 1.3 µm Sa, as illustrated in Fig. 29 [132]. Utilizing a design matrix with 17 factors and 50 levels, this study innovatively optimizes conformal cooling channels in hot stamping tools, focusing on three key design variables, and employing multi-objective optimization to identify the Pareto optimal frontier for optimal combinations, thus achieving enhanced cooling performance [133]. This research introduces a comprehensive lifecycle assessment method to appraise the total energy demand of traditional and conformal cooling molds. The findings suggest that, despite the higher initial energy costs for conformal cooling molds, a positive energy balance is achievable after a certain payback period, which is dependent on the enhanced energy efficiency of the injection molding process [134]. Research employs Selective Laser Melting (SLM) to construct conformal cooling channels in injection molding tools for a plastic part used in the medical industry. The results indicate a substantial reduction in cooling time and cycle time without sacrificing part quality, leading to potential energy savings, scrap minimization, and enhanced productivity [135].

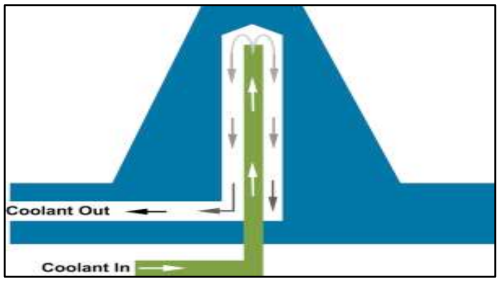


Fig. 30 Illustration of typical bubbler cooling for mold core [136]

Study describes a practical method for creating molds with conformal bubbler cooling channels as shown in Fig.30 using a hybrid metal deposition machine. This can reduce cycle time, energy consumption, and increase production rates [136]. Hybrid tool designs have also been explored, combining CCCs and heat-conducting copper inserts, leading to improved cooling efficiency and smoother temperature distribution in injection molding processes [137]. Research explores the intricate process of utilizing Metal Additive Manufacturing to optimize conformal cooling channels in plastic injection molds, addressing complexities and multiple design variables to enhance cooling performance and achieve design efficiency. The comprehensive study spans computer-aided design, multi objective optimization, and meticulous quality checks, demonstrating the potential of this approach in balancing design flexibility and efficiency in manufacturing processes [138]. An optimization method for determining sheet thicknesses in laminated tooling to cut down manufacturing costs and improve cooling performance. Leveraging a genetic algorithm, the optimized set of available sheets showcases decreased post-processing cost and improved cooling performance compared to traditional cooling channels [139]. This study outlines a method for manufacturing profiled conformal cooling channels in aluminium-filled epoxy molds using rapid prototyping and rapid tooling techniques. This innovative design can lead to decreased cooling times in the injection molding process and superior heat dissipation, enhancing overall process efficiency [140]. The study demonstrates the impact of conformal cooling channels on welding performance, showing improved hardness around the weld joint and reduced residual stress levels using the laser powder bed fusion approach [141].The study introduces a green conformal cooling system that reduces cycle time by 66%, temperature gradient by 78.5%, residual stress by 81.88%, and warpage by 90.5% [142]. The development of hot embossing stamps with conformal cooling channels, achieving a notable 92% reduction in cooling time and a 72% decrease in manufacturing costs compared to traditional stamps, by utilizing innovative rapid prototyping and tooling techniques [143]. Using various cooling-channel designs, this study significantly reduced cooling times by 92% in aluminium-filled epoxy resin hot embossing stamps. This innovative approach also led to a 72% reduction in manufacturing costs [144].

4.3 Conformal Cooling Channel Performance and Optimization

The optimization and effectiveness of conformal cooling channels in injection molding tools have been the subject of recent investigations. Utilizing finite element analysis and thermal heat transfer analysis, a notable decrease in cycle time and an improvement in surface finish quality have been detected compared to traditional molds [145]. The incorporation of conformal cooling channels into standard dies, with features such as a 6mm diameter channel, an 8mm pitch distance, and a 4mm channel wall distance from the mold wall, has been shown to enhance cooling performance [146]. This study introduces an advanced method, leveraging 3D printing and CAE simulation, to optimize conformal cooling channels in injection molding, achieving over 50% reduction in cooling and cycle time compared to traditional channels and enhancing molded part quality. This innovation stands as a substantial contribution to eco-friendly manufacturing, promoting energy efficiency in the injection molding production process [147].

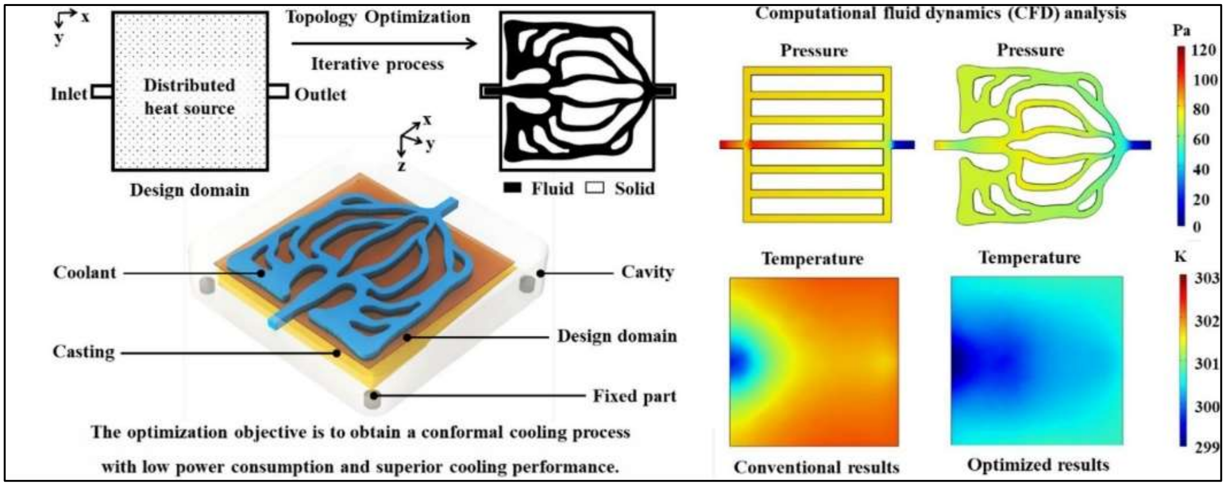


Fig. 31 Showing the comprehensive performance enhancement of the conformal cooling process through thermal-load-based TO [148]

In casting processes where uneven thermal loads are considered, the average temperature and pressure drop have been shown to decrease by as much as 1.45 K and 27.55%, respectively. Both sheet and cylindrical casting results have showcased the stability, versatility, and logic of the proposed method. The conceptual design of cooling channels based on thermal load is anticipated to be employed in more potential thermal zones, as shown in Fig.31 [148]. A sophisticated topology optimization approach to design conformal cooling systems in injection molding, focusing on refining channel networks and addressing challenging cooling areas, thus improving efficiency and uniformity in the cooling process. The innovative methodology, utilizing the cycle-averaged approach and boundary element method (BEM), presents a significant advancement in optimizing and refining cooling processes in injection molding applications [149]. A holistic approach to designing conformal cooling channels in injection molds through a coupled thermal-fluid topology optimization algorithm, transitioning from conceptualization and 3D printing in Maraging Steel to real-world industrial testing, enhancing thermo-fluid performance and product quality. The comprehensive study provides pivotal insights and practical recommendations, enabling the injection molding industry to optimize additive manufacturing techniques and implement advanced design methods for significant benefits in industrial production scenarios [150]. This study introduces optimized molds with 59.1% and 50.5% porous structures for cavity and core, enhancing performance and reducing costs while incorporating conformal cooling channels for batter thermal management [151]. This study comprehensively validates the superior cooling performance of conformal cooling channels in plastic injection molding, demonstrating a significant reduction in cycle time and warpage compared to conventional channels through numerical simulations and experimental results. The advancement of using additive manufacturing technology to develop these channels marks a pivotal step in optimizing and enhancing the efficiency and quality in the manufacturing process. [152]. The use of selective laser sintering technology in injection molds has been shown to boost the efficiency of conformal cooling channels. By combining analytical formulas and CAE simulation, the cooling time and cycle time have been reduced by over 50% compared to traditional straight-drilled cooling channels, making a significant contribution to eco-friendly manufacturing technology [153]. A set of design methodology and guidelines for conformal cooling channels in injection molds, aimed at enhancing the quality and productivity of injection-molded parts [154]. Utilizing finite element analysis for optimizing mold design with conformal cooling channels has led to a reduction in cooling time by up to 50%, thereby significantly enhancing production rate and quality [155]. This focus on optimization also extends to the reduction of warpage in front panel housing parts with MGSS conformal cooling channels, where the use of RSM optimization led to a reduction by 38.7% [156]. In the realm of plastic injection molding, strategies to optimize the process and enhance outcomes have been thoroughly explored. study employed a genetic algorithm and Moldflow to optimize and simulate the injection process parameters for a bowl-shaped product made of PP AZ564. The results showed that the optimal parameters resulted in a cycle time of 14.11 sec., corroborated by experimental results with an average cycle time of 14.19 sec. a difference of less than 1% [157]. A multi-objective optimization approach can minimize warpage, clamping force, and cycle time in plastic injection molding using conformal cooling channels. This has resulted in a 43% reduction in warpage, a 1.7% reduction in clamping force, and a 47% reduction in cycle time. Notably, the application of optimization algorithms in the design of these channels has yielded remarkable improvements in surface temperature differences of up to 45.5% and has successfully mitigated lens warpage, thus enhancing the optical properties of plastic lenses [158]. This improvement in cooling and reduction of defects in the injection molding process has been supported by findings from finite element analysis and Taguchi method [159]. In another study, bi-metallic CCCs with high thermal conductive copper tube inserts resulted in a 35% reduction in cooling time and increased fatigue life, indicating the potential for enhancing productivity [160].

Investigation revealed that conformal cooling channels, optimized with the help of computer-aided engineering tools, offer superior and more evenly distributed cooling compared to conventional cooling lines in injection molding. The outcome manifested as a drop in part temperature by 6-7°C for HDPE and 7°C for PC, indicating the possibility for reducing cooling time [161]. Hu et al.'s 2016 study on cooling performance in hot stamping tools, specifically the optimal Reynolds number for conformal cooling channels. While the original study proposed an optimal value of 100,000, which might induce significant pressure drops, this investigation recommends a more feasible 20,000 based on consistent numerical simulations and supporting references [162].

5. Conclusion

As plastics technology continues its rapid evolution, the significance of understanding material properties, processing, and cooling techniques cannot be overstated. This review has underscored the diversity of molding techniques and their intricate interplay with material performance. The introduction of novel approaches and innovations in the material sector, especially with respect to environmental considerations, marks a promising stride towards sustainable plastics technology. On the processing front, the emphasis on optimization strategies and the integration of real-time monitoring technologies elucidates the direction in which the industry is headed. Cooling, particularly the design and optimization of conformal cooling channels, emerges as a vital component in ensuring efficient plastics production. In summation, as the field of plastics technology progresses, a harmonious amalgamation of material science, processing methodologies, and cooling strategies will be imperative for achieving excellence and sustainability. As the contours of this field continue to evolve, the insights and revelations garnered here will be instrumental, guiding the next generation of research and applications, propelling the industry towards a future marked by sustainability, innovation, and excellence.

The convergence of material science, robotics, and digital technologies could lead to the creation of smart plastics with embedded electronics or those that can change shape or properties on demand. In essence, the future of plastics technology is poised at an exciting juncture. Collaborative efforts, technological innovations, and a commitment to sustainability will shape the trajectory of research and applications in the forthcoming decades. In light of the above, it's evident that the field of plastics technology is set to witness a confluence of interdisciplinary research, with a strong focus on optimizing material properties, processing techniques, and cooling strategies while keeping sustainability at the forefront.

6. Future Scope

The horizon of plastics technology is vast and rife with potential. As we reflect upon the advancements detailed in this review, several avenues for future exploration and research emerge:

- With the advent of nanotechnology and bioplastics, the coming years could witness a surge in research focusing on integrating these technologies to enhance the mechanical and thermal properties of plastics. The potential for self-healing plastics or those with embedded sensors might redefine the boundaries of material science.
- As environmental concerns intensify, the development of sustainable and biodegradable plastics will likely take centre stage. Research into plastic alternatives derived from biomass or the recycling of plastics at the molecular level could revolutionize the industry's environmental footprint.
- The integration of artificial intelligence and machine learning in processing could usher in an era of predictive modelling, real-time adjustments, and enhanced optimization, ensuring consistent quality and efficiency.
- With the increasing demand for precision in manufacturing, research into adaptive cooling systems that can dynamically adjust based on real-time feedback might become pivotal.

- Given the mention of environmental considerations in material innovations, there is an evident scope for research into plastics that are not only high-performing but also environmentally benign or recyclable.

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