

Additive Manufacturing: A Key to Advancing Injection Molding Efficiency

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Abstract: The increasing demand for custom-made products, small-batch production, and improved process efficiency is driving manufacturers to adopt advanced strategies that minimize costs and production time. Additive manufacturing (AM) technologies address these challenges by enabling rapid prototyping, design flexibility, and advanced tooling capabilities. Initially constrained to polymeric prototypes, AM now supports a diverse material range, including metals and temperature-resistant polymers. Injection molding is a widely used manufacturing process for producing plastic parts with high precision and repeatability. However, traditional injection molding faces challenges such as high tooling costs, long lead times, and design limitations. This paper investigates solutions to these challenges through the application of additive manufacturing and rapid tooling technologies, emphasizing their potential to transform efficiency in injection molding.

Keywords: additive manufacturing; conformal cooling channels; injection molding; rapid prototyping

1 INTRODUCTION

The manufacturing industry has witnessed transformative changes in recent decades, with the integration of advanced technologies playing a pivotal role in improving efficiency, reducing costs, and enabling innovation. Among these technologies, Additive Manufacturing (AM), also known as 3D printing, has emerged as a transformative force that is reshaping traditional production processes. Initially developed as a prototyping tool, AM has evolved into a robust and efficient technology capable of rapidly producing fully functional end products (additive/direct manufacturing) and tooling components (rapid tooling) [1, 2]. It offers advantages such as shortened lead times, cost savings, and enhanced design flexibility, alongside a broad material selection, including polymers, metals, ceramics, and composites, all while minimizing material waste [3]. On the other hand, the main challenges of AM technologies involve limitations in part accuracy, surface quality, strength, durability, size, and production speed.

The term rapid tooling (RT) encompasses processes that employ AM technologies to produce tooling components, including cavities, cores, inserts, dies, molds, ejectors, sliders, gauges etc. While RT is sometimes considered a distinct application level within AM technologies, it is not entirely independent [4]. RT eliminates many of the bottlenecks associated with conventional tooling production, such as extended lead times and high total costs.

There are two main levels of AM application in tooling production, based on tool quality and functionality: Hard Tooling (HT) and Soft Tooling (ST). HT involves creating fully functional tools for high-volume production directly from CAD models using AM and high-strength materials such as steel and aluminium. This approach enables the fabrication of highly complex mold shapes with enhanced durability. ST includes tools designed for single or small-batch production. Soft tooling, commonly made from substitute materials, generally does not match the durability of hard tooling but offers significant cost savings. This makes it a practical choice for applications involving frequent design changes or low-volume production requirements. For

instance, in injection molding, a soft tool typically lasts between 100 and 1,000 shots [5, 6]. Fig. 1 provides a graphical representation of the number of cycles for molds produced using conventional tooling as well as AM-based technologies, plotted against the workpiece material. In some cases, ST tools are categorized as a subset of HT tools and referred as Bridge Tools (BT) [3]. In general, the quality of rapid tooling produced through AM is primarily determined by two factors: the material used and the AM technology employed. It is important to note that HT and ST do not mean the entire tool assembly is made via AM. Typically, only specific, non-standard tool components are manufactured using AM and then combined with conventional tool elements to form a complete, functional assembly.

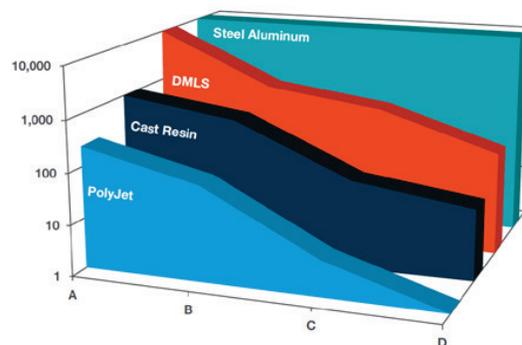


Figure 1 The number of parts manufactured using molds produced by conventional and AM technologies [8] (A - PE, PP, PS, ABS, TPE; B - PP+G, PA, POM, PC+ABS; C - PA+G, PC, POM+G; D - PC+G, PPO, PPS)

The ISO/ASTM 52900 standard [7] classifies AM technologies into seven distinct families or categories, each defined by the fundamental process used to build parts. These categories encompass a wide range of techniques, including material extrusion, powder bed fusion, vat photopolymerization, binder jetting, directed energy deposition, sheet lamination, and material jetting. However, not all AM methods are suitable for producing tools and tooling components. Each AM technology comes with its own advantages and limitations, which can substantially influence the final tool's performance and service life. Selecting the optimal AM technology depends on the type of

tool and the associated techno-economic requirements. It is important to note that AM molds must meet far more rigorous standards than conventional AM components to withstand the intense mechanical and thermodynamic loads during use.

HT, which involves the production of tool components from metal materials, commonly utilizes AM technologies such as Selective Laser Melting (SLM), Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), and Directed Energy Deposition (DED). On the other hand, ST components, primarily made from polymeric materials, are typically manufactured using Stereolithography (SLA), Digital Light Processing (DLP), Selective Laser Sintering (SLS) and, PolyJet techniques.

This paper provides an in-depth analysis of the benefits AM brings to injection molding processes and presents selected results from its application in mold production. Additionally, it highlights challenges of applying AM in mold manufacturing.

2 OVERVIEW OF THE BENEFITS OF IMPLEMENTING AM TECHNOLOGIES IN INJECTION MOLDING TOOLING

Injection molding is a widely used manufacturing process, renowned for its ability to produce high volumes of complex plastic parts with consistent quality. However, it is not without its challenges. The process often involves significant lead times, high tooling costs, and limited flexibility for design modifications, which can hinder manufacturers' ability to respond quickly to market demands and innovation opportunities. AM addresses these challenges by providing innovative solutions that enhance the efficiency and adaptability of injection molding processes.

2.1 Fast Mold Prototyping and Enhanced Small-Batch Production Efficiency

AM allows manufacturers to quickly prototype molds and components, enabling rapid iteration and testing. This significantly reduces the time between design and production, allowing manufacturers to respond more flexibly to market demands and reduce the risk of costly errors. According to Whelan and Sheahan [9], the use of AM/RT can reduce product development costs by up to 70% and decrease time to market by as much as 90%. Levy et al. [5] presented similar findings, demonstrating that the application of AM in producing mold components, such as core and cavity, led to a 50–70% reduction in both the time and cost associated with mold development and design. The ability to easily modify mold designs and create customized solutions also opens up opportunities for smaller production runs and more tailored products. This is particularly beneficial for industries such as healthcare and aerospace, where custom components are often required. AM also supports on-demand mold production, a crucial advantage for industries that require custom components. In other words, AM and RT have the potential to resolve the challenges encountered by design engineers and manufacturers in balancing part design, manufacturability, and small-batch production.

2.2 Improvements in Mold Design, Manufacturing, and Performance

One of the most significant contributions of AM to injection molding is in mold design [3, 9]. Conventional injection molds require a substantial investment of time and resources to design and manufacture. The process often involves CNC machining, which can be limited by the complexity of mold features and the time required for tool manufacturing. AM, however, allows for advanced mold designs and the production of molds with complex geometries and cooling structures that are difficult or impossible to achieve with conventional techniques [2]. This includes complex cores and cavities, conformal cooling channels, intricate lattice structures, and lightweight features. As a result, cycle times are shorter, warping is minimized, part quality is improved, and scrap rates are reduced.

2.3 Reduction in Mold Weight

Large molds are commonly used in industries such as automotive, aerospace, and household goods [10]. However, their size and complexity introduce significant challenges, including excessive weight, high unit costs, and safety risks. The use of AM-created lattice structures has emerged as a promising solution for reducing mold weight while maintaining mechanical strength and functionality.

2.4 Multi-Material Printing and Material Efficiency

AM enables the simultaneous printing of molds using multiple materials [4], a capability particularly valuable when different regions of a mold require distinct properties. Multi-material printing facilitates the integration of characteristics such as varying hardness, thermal conductivity, or wear resistance. For instance, a mold may feature a hard, durable surface in high-wear areas while incorporating a softer, more flexible material in sections requiring intricate detail.

In terms of material efficiency, AM provides a significant advantage over traditional machining by substantially reducing material waste. Material waste can be cut by up to 90% with AM [1, 11], making it a more sustainable and cost-effective manufacturing method.

2.5 Mold Maintenance and Repair

AM can be employed to repair or modify molds, effectively extending their operational life and reducing downtime [6]. By using AM, damaged areas of molds can be accurately repaired, and design updates can be seamlessly integrated without requiring complete tool replacement.

2.6 Smart Molds

Using AM technologies, sensors and heating elements can be seamlessly incorporated into the mold structure without compromising its durability or functionality [12]. These features provide real-time monitoring and control of the molding process, including temperature, pressure, and flow rates, to maintain optimal production conditions.

2.7 Hybrid Manufacturing

The integration of AM with conventional manufacturing methods provides innovative solutions for enhanced efficiency. By utilizing AM to produce near-net-shape molds and CNC machining for final finishing, complex geometries can be created with minimal material waste while achieving high accuracy and superior surface quality in critical areas.

3 SOFT AND HARD TOOLING SOLUTIONS FOR MOLDING

In prototype and low-volume production (soft tooling), a universal metal base combined with polymer-based inserts (core and cavity) is commonly used. This modular approach allows a single master base to support multiple insert designs. Additionally, the robust metal base enhances structural integrity, enabling a reduction in the size of polymer core and cavity inserts, which results in faster production and reduced material waste. To optimize the performance of polymer inserts, the mold base geometry should be slightly adjusted compared to designs intended for metal inserts. Mold features such as draft angles, radii, and gate size should be increased as much as possible, while sprue and ejector holes should be undersized by 0.2-0.3 mm. As for runners and cooling channels, standard sizing practices should be followed when dimensioning [2].

Molds with polymer inserts are not without limitations. While they are well-suited for prototyping, low-volume production, or specific applications where extreme durability is not required, they may not withstand the high pressures and temperatures associated with large-scale or high-volume part manufacturing as effectively as metal molds. Therefore, one of the key challenges in developing an AM process for molds with polymer inserts is selecting materials that provide the necessary mechanical and thermal properties of mold. The differing thermal responses of polymers inserts during the injection and cooling stages require precise control to avoid tolerance loss and deformation of the workpiece. The service life of a polymer mold depends on several factors, including the mold material, the complexity of the tool /workpiece geometry, melted polymer properties, injection molding process parameters, wear etc. Another challenge in AM molds is surface quality, as the layer-by-layer manufacturing process can introduce roughness that necessitates additional finishing steps.

In addition to the previously mentioned drawbacks, polymer molds also provide several advantages over metal molds, including: reduced clamping force, improved air barrier performance, and better ventilation. Ventilation conditions can be further optimized with the use of multi-part molds (Fig. 2), which improve their service life [8]. Multi-part molds are particularly beneficial for molds with complex geometries, where damage to individual segments can occur due to small sections and sharp corners. Additionally, they offer the advantage of quick replacement if individual components break or deform. To enhance the operational performance of molds with polymer inserts and extend their service life, it is crucial to carefully select injection molding process parameters, including temperature, pressure, and

cycle time. In other words, adjustments to the parameters used for conventional (metal) inserts should be made, and their upper limits must be defined to prevent mold damage. In general, it is recommended to select standard processing parameters for injection pressure, mold temperature, and melt temperature of industrial polymers at the lower end of the recommended ranges. In terms of injection pressure, the rate at which it increases is also important. Applying the standard injection pressure adjustment procedure, which involves a rapid increase to maximum pressure, could result in the displacement of inserts and their undesirable deformations, leading to improper mold functioning. Therefore, the injection pressure should be gradually increased and generally kept as low as possible. Similar recommendations apply to the holding pressure.

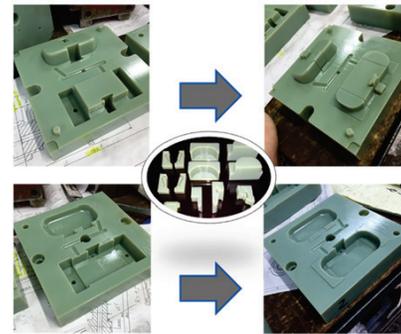


Figure 2 Multi-part molds produced using the PolyJet process [8]

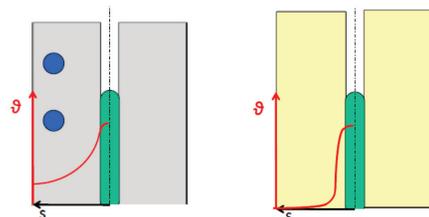


Figure 3 The temperature profiles of the metal (left) and polymer (right) molds [13]

Cooling time is another critical factor, as it directly affects both the efficiency of the injection molding process and the service life of the mold. Due to the lower thermal conductivity of molds with polymer inserts compared to traditional metal molds, the cooling time is significantly longer to prevent thermal damage to the molds. Fig. 3 illustrates the temperature distribution across the cross-section of conventional (metal) and polymer mold inserts. As seen in Fig. 3, heat distribution is more uniform in the metal insert (Fig. 3 - left) compared to the polymer insert, where heat accumulates near the mold parting line. This leads to a higher thermal load on the insert surface, increasing wear and sticking while raising the risk of warping or cracking. To minimize wear, it is crucial to extend the cooling phase (time) after part ejection and, if possible, reduce the wall thickness. On the other hand, a slow cooling rate increases the crystallinity of the molded part, enhancing its strength, dimensional stability, and aesthetic appearance. Besides this, slower cooling contributes to lowering internal stresses, ensuring improved strength and reliability of the molded part. In this regard, polymer molds offer advantages over metal

molds. It is important to note that cold compressed air is commonly used during the open mold time to keep mold insert temperatures below the heat deflection temperature (HDT). This approach offers greater cooling efficiency compared to traditional cooling channels, which may compromise the stiffness of a polymer mold.

Fused Deposition Modeling (FDM) is the most accessible form of 3D printing. Although FDM employs a wide range of materials, only a few materials, such as Acrylonitrile Butadiene Styrene (ABS), ABS-X, Acrylonitrile Styrene Acrylate (ASA), PolyEther Ether Ketone (PEEK), Polyether Imide (PEI) - ULTEM, and several nylons, meet the operational demands of injection molding. Furthermore, producing parts from these materials requires specialized printer capable of achieving high nozzle temperatures (above 300 °C), heated build plates (above 100 °C), and, in some cases, a high ambient temperature of over 170 °C [14]. Despite its advantages, FDM-based mold manufacturing faces notable obstacles, such as high surface roughness and structural weaknesses in the gate area, which experiences extreme thermal and pressure conditions. As a result, these inserts typically last no more than 10 injection molding cycles before sustaining damage, primarily at the gate. In contrast, tools and molds produced using SLA, DLP, and SLS exhibit greater resistance to high temperatures and pressures. While all these methods enhance mold durability, SLA and DLP offer a smoother surface finish compared to SLS, typically requires. Moreover, SLA and DLP are generally more cost-effective, making them a more attractive option for various applications.

In its early stages, SLA was mainly used to create solid resin molds for prototyping and small-scale production (up to 50 pieces) of simple, small components made from low-abrasion, low-melting-point thermoplastics. This process is known as direct SLA or Accurate Clear Epoxy Solid (ACES) injection molding (AIM) tooling, where both the core and cavity are fabricated directly using a stereolithography machine. Thanks to advancements in SLA resin technology, primarily through the introduction of acrylic, vinyl, and epoxy-based resins that can withstand higher operational temperatures, SLA has significantly enhanced its ability to produce mold inserts with improved performance and longer service life (up to 200 cycles), as well as to mold parts from a wider range of materials. SLA mold production has been further enhanced with the introduction of shell tooling, commonly referred to as backfilled molds. This process begins with the creation of an SLA shell with a wall thickness of 2–3 mm, which is then reinforced with thermally conductive materials such as aluminum-filled epoxy (a blend of 70% epoxy resin and 30% aluminum powder) or a low-melting metal alloy to form the injection molding tool (Fig. 4). This mold not only provides improved thermal conductivity and service life (allowing for 50–500 cycles of materials at melting temperatures up to 300 °C) but also reduces tooling development costs compared to molds produced using the direct SLA method.

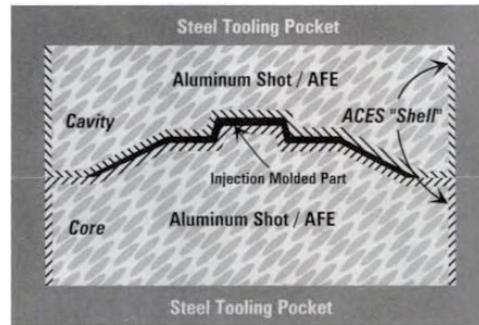


Figure 4 Cross section of backfield mold [13]

Similar to SLA, PolyJet mold inserts are most effective for thermoplastics that melt at low to moderate temperatures (below 300 °C) and demonstrate excellent flow characteristics, including polyethylene (PE), polypropylene (PP), polystyrene (PS), acrylonitrile butadiene styrene (ABS), thermoplastic elastomers (TPE), polyamides (PA), polyoxymethylene (POM), PC-ABS blends, and glass-filled resins [15]. PolyJet molds are best utilized in small-batch production (typically 5 to 100 molded parts - see Fig. 1) and for small to medium-sized components with volumes up to approximately 150 cm³. The poor heat conductivity of PolyJet molds limits the effectiveness of cooling systems in reducing molding cycle times or improving part quality, but they can extend tool life by up to 20% [15]. This improvement is more noticeable as the cavity depth and core height decrease. Mendible et al. [16] compared conventionally manufactured metal inserts to those made using DMLS (metal) and PolyJet (polymer) technologies, as shown in Fig. 5. The findings reveal that DMLS inserts closely matched the performance of machined inserts, with no evident signs of failure after 500 cycles. In contrast, PolyJet inserts began producing defective parts at 80 cycles and failed completely by 116 cycles. Additionally, PolyJet mold exhibited the highest shrinkage variance, along with extended cycle times and notable temperature gradient.

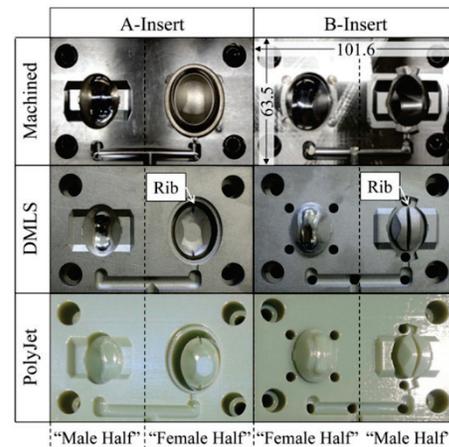


Figure 5 Mold inserts manufactured using different technologies [16]

In injection molding process, the reduction in cycle time is heavily influenced by the design (conformability) of the cooling channels and the complexity of the part. Unlike traditional straight-line cooling channels, conformal cooling

channels (CCCs) are designed to follow the contours of the mold, ensuring more uniform heat removal and efficient cooling. This results in shorter cycle times and enhanced production efficiency. According to studies [6, 10, 17], conformal cooling channels (CCCs) can reduce cycle times by up to 50%, with certain applications reporting reductions of up to 70%, as noted by Evens et. al. [18]. These channels also enhance surface finish quality, minimize shrinkage and deformation, reduce the average time required to reach ejection temperature by over 30% compared to conventional cooling methods, and lower the maximum temperature on the mold surface by up to 20-30% [19].

One of the key advantages of CCCs is their ability to provide a more uniform temperature distribution across the mold surface, effectively reducing hot spots - localized areas with elevated temperatures that can negatively impact product quality. By optimizing heat dissipation, CCCs contribute to improved dimensional stability and reduced internal stresses within molded parts. In terms of economic benefits, a 20–40% reduction in cooling time can result in an estimated 27–55% increase in profit margins. Additionally, product quality improvements of up to 70% have been reported when CCCs are implemented in the injection molding process [17].

However, while CCCs enhance cooling efficiency, their complex design can introduce challenges. The intricate pathways result in higher coolant pressure drops than conventional channels, leading to increased energy consumption from the cooling system. This trade-off between cooling time reduction and temperature uniformity underscores the importance of proper CCC design and optimization before real-world implementation.

The CCCs are predominantly integrated into molds that feature metal inserts (core and cavity), which are manufactured using AM powder bed fusion (PBF) technologies. In addition to common PBF-related challenges such as porosity, residual stresses, and rough surfaces, a critical concern in manufacturing molds with CCCs is the risk of collapse and warping of overhanging structures, particularly in large holes and channels. To ensure structural integrity during printing, support structures are often required. However, removing these supports and clearing residual powder from internal channels can be difficult due to their complex geometries and small diameters. If left inside, they can obstruct coolant flow and reduce cooling efficiency. To address this issue, molds featuring self-supporting CCCs and tailored porous structures, incorporating high-strength diamond units, have recently been designed and manufactured (Fig. 6) using AM-PBF technology [20].

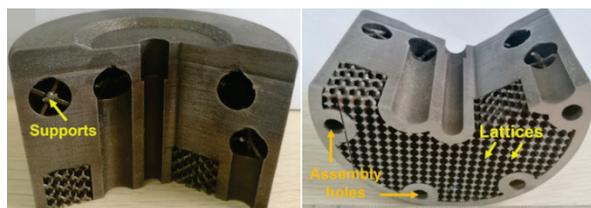


Figure 6 Mold with self-supporting CCCs and porous structures [21]

As it said before, AM technology allows for the precise design and fabrication of complex lattice structures that optimize material distribution within the mold. Study [21] confirmed the effectiveness of lattice structures in reducing mold weight, achieving an impressive 79% reduction compared to a solid Ti-6Al-4V mold using octet-truss (OT) and diamond (DM) configurations (Fig. 7). The redesigned mold also proved highly durable, completing 400 PVC injection cycles without any visible damage. Furthermore, lattice structures can be utilized to enhance both the structural integrity and thermal management of molds. By incorporating conformal cooling layers (Fig. 8) composed of interconnected scaffolds or porous elements, these structures enable heat transfer fluids to flow as close as possible to the molding surface. [22, 23]. Brooks et al. [23] found that conformal cooling layers can reduce cooling time by up to 27% compared to conventional cooling channels.

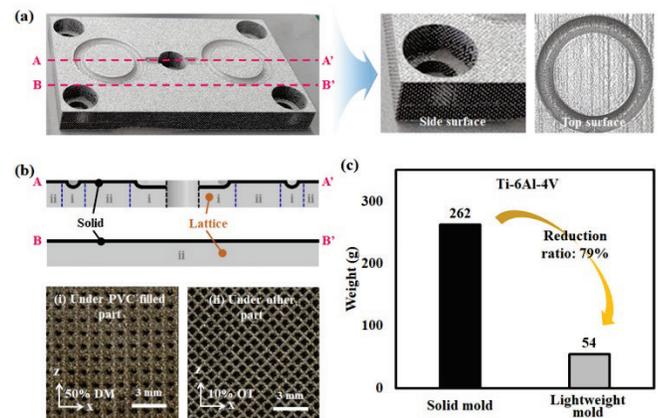


Figure 7 Additively manufactured mold with a lattice structure (a), sectional view illustrating step height (b), weight comparison between solid and lightweight Ti-6Al-4V molds (c) [22]

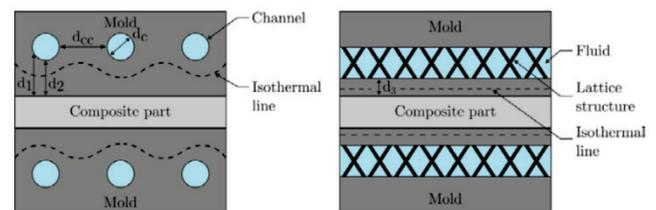


Figure 8 Schematic representation of (a) conventional cooling channels and (b) conformal cooling layers. [23]

4 CONCLUSION

Technological advancements in AM and RT have the potential to reshape the injection molding industry. By enhancing mold design, reducing prototyping time, and improving production efficiency, AM is addressing many limitations of traditional mold manufacturing. However, challenges remain. The durability of 3D-printed molds for high-volume production is still a concern, and the high cost of advanced AM systems can be a barrier for smaller manufacturers. Additionally, AM metal molds often require post-processing to achieve the required surface finish and dimensional accuracy.

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