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Original article

SLA-Based Injection Molding Tool Inserts: Challenges, Innovations, and Future Prospects

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ABSTRACT

Stereolithography (SLA), a key technology in additive manufacturing, has transformed the production of injection molding tool inserts by enabling rapid prototyping and cost-effective small-scale production. SLA utilizes photopolymer resins to fabricate intricate, high-precision molds, reducing lead times and costs. However, challenges such as limited mechanical strength, lower thermal resistance, and slower heat dissipation compared to traditional materials constrain its broader adoption. This paper reviews the application of SLA in injection molding, emphasizing advancements in high-performance resins that improve durability, thermal stability, and mechanical properties. Key factors affecting mold performance, including material flowability, cooling times, and injection pressure, are discussed alongside optimization strategies like modular designs and post-processing techniques. While SLA molds may not rival traditional tools for high-stress applications, they excel in rapid tooling and prototyping. As material and process innovations continue, SLA is poised to play a transformative role in modern injection molding, bridging additive and traditional manufacturing.

Key words: *stereolithography; injection molding; additive manufacturing; rapid tooling;*

1. INTRODUCTION

Additive manufacturing (AM), widely recognized as 3D printing, has fundamentally transformed the manufacturing industry by enabling the creation of intricate geometries with exceptional precision, customization, and efficiency. Among the diverse array of AM technologies, Stereolithography (SLA) has emerged as a leading method, renowned for its ability to fabricate highly detailed and accurate parts. Since its development in the 1980s, SLA has undergone significant advancements in terms of technology, materials, and accessibility, establishing itself as a pivotal tool in modern manufacturing.

Injection molding remains one of the most widely used techniques for the mass production of plastic components, offering scalability and consistency. However, the traditional fabrication of mold inserts for injection molding—relying heavily on CNC machining and electrical discharge machining (EDM)—often involves high costs and extended production timelines, particularly for complex or low-volume designs. These challenges have spurred interest in alternative methods, and SLA has emerged as a promising solution. Its capability to rapidly produce mold inserts with fine details, intricate features, and smooth surface finishes positions it as a disruptive force in this domain.

This paper explores the application of SLA in the additive manufacturing of injection molding tool inserts, emphasizing the technological advancements, innovative material developments, and process enhancements that have expanded its capabilities. By leveraging SLA, manufacturers can reduce lead times, lower costs, and

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enable greater design flexibility. However, the technology is not without its limitations, such as material durability and thermal resistance, which remain critical areas for improvement. Through an analysis of recent research and case studies, this paper aims to provide a comprehensive understanding of how SLA can be effectively utilized in injection molding applications, highlighting its transformative potential and the challenges that need to be addressed for wider industrial adoption.

2. SLA RAPID TOOLING

Additive manufacturing, widely acknowledged for its ability to produce complex and customized components, offers transformative advantages in scenarios involving small-scale or customized production runs [1]. Compared to traditional injection molding, AM excels in flexibility, cost-effectiveness, and shorter lead times, particularly for prototype development and low-volume manufacturing. In tooling, AM enables faster market introduction of new products with minimal capital investment and lower fixed costs, significantly enhancing production agility. The concept of rapid tooling, a key innovation within AM, has been pivotal in driving the evolution of modern manufacturing by streamlining the tooling development process [2]. Since its recognition in 1995 for its cost-reduction potential, rapid tooling has emerged as a cornerstone of manufacturing strategies. Classification of rapid toolig is given in Fig.1.

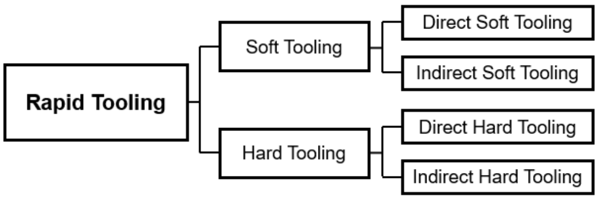
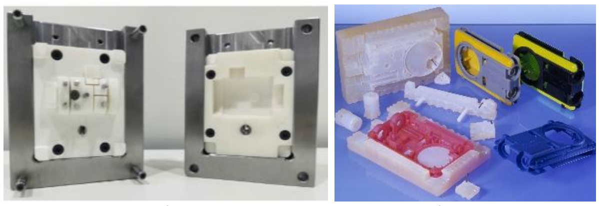


Fig. 1 Classification of rapid tooling [3]

Rapid tooling encompasses diverse AM applications for the fabrication of tools, tool inserts, gauges, and molds [4]. Its defining attribute lies in its ability to produce functionally viable prototypes and production tools with significantly reduced lead times, a capability that has reshaped traditional production workflows. As depicted in Figure 1, rapid tooling is classified based on application and production methodology.

Within rapid tooling, Stereolithography (SLA) plays a critical role, particularly in the production of direct soft tooling. This category involves the creation of tooling inserts directly from AM processes using non-metallic materials, such as light-reactive photopolymers. SLA-produced inserts are particularly suited for small batch or single-use applications, offering advantages like rapid turnaround and lower production costs. However, these tools often suffer from limited mechanical and thermal durability, necessitating careful application selection and ongoing material advancements.

Tooling approaches can be classified into direct and indirect methods. Direct tooling involves the direct fabrication of the entire mold geometry using AM technologies, whereas indirect tooling employs AM to create a master pattern used for subsequent mold manufacturing. Examples of indirect tooling include epoxy or silicone molds cast around master patterns, as illustrated in Fig. 2. Each approach offers unique benefits and trade-offs, highlighting the versatility of AM in tailoring solutions for specific manufacturing needs.



a) b)

Fig. 2 Direct (a) and indirect (b) soft tooling; a) SLA molding inserts; b) silicon molds; [5], [6]

3. LITERATURE REVIEW ON THE APPLICATION OF SLA IN INJECTION MOLDING TOOL DESIGN

SLA has emerged as a prominent method in the production of injection molding tool inserts due to its ability to produce highly precise and complex tool geometries with relatively short lead times. There are several different RT processes for obtaining prototypes explained by *Gebhardt* [7] and *Radstok* [8]. In previously published literature ([9], [10]), several general comparisons of RT technologies have been made, but they mostly focus on the number of pieces that can be obtained and the savings in time and costs compared to conventional tools.

Harris et al. ([11], [12], [13]) have conducted extensive research on the use of SLA for injection mold tooling. Their studies highlight several key factors that influence the performance of SLA tools, including layer thickness, draft angle, and the thermal properties of the mold materials. The studies investigate the impact of layer thickness and draft angle on the ejection forces in SLA injection mold tooling. The results indicate that a larger layer thickness leads to higher surface roughness, which in turn increases the ejection force required. The draft angle was found to have a linear relationship with the ejection force, where increasing the draft angle reduces the ejection force needed. The research emphasizes the importance of optimizing these parameters to minimize the risk of tool failure during the injection process.

Harris et al. [13] also explore the shrinkage behavior of polymers molded using SLA tools compared to conventional aluminum tools. Their findings reveal that the thermal properties of the SL epoxy molds result in different cooling rates, leading to varying shrinkage rates in the produced parts.

Volpato et al. [14] examine the application of Digital ABS [15], a material developed by Stratasys, in RT for injection molding. The study finds that Digital ABS exhibits stable dimensional behavior during the injection molding process. The inserts maintain their dimensions after multiple injection cycles, with only minor changes in length, width, and depth. The mechanical properties of parts molded with Digital ABS inserts were found to be comparable to those molded with traditional metal inserts. Tensile, bending, and impact tests showed that the differences in properties were minimal, demonstrating the viability of Digital ABS as an RT material.

Studies like those by *Hopkinson* and *Dickens* ([16], [17]) demonstrate that while SLA and PolyJet molds are suitable for rapid tooling, they often suffer from low material strength and poor thermal conductivity. These weaknesses lead to problems such as tensile failure and increased cycle times during molding, especially under high temperatures during injection molding.

In the study by *Tábí* et al. [18], the mechanical and thermomechanical properties of PLA injected into both PolyJet and steel molds were compared. The results showed that the choice of mold material significantly affects the crystallinity of PLA parts, which in turn impacts their mechanical properties. For PLA, molds with better thermal conductivity (such as steel) allowed for higher crystallization and improved part performance.

Bagalkot et al. [19] categorize the different failure modes of SL inserts for injection molding. These include surface deterioration, bending, shear, and edge failure. Factors such as injection pressure, melt temperature, and mold material thermal properties play a significant role in tool life and part quality. The study emphasized the importance of process optimization to mitigate failures and extend the life of SL tools.

4. STEREOLITHOGRAPHY PROCESS FUNDAMENTALS

Stereolithography (SLA) is one of the pioneering and most extensively utilized technologies in additive manufacturing. Its unique approach to layer-by-layer fabrication has made it a cornerstone in the AM landscape, particularly for producing high-resolution components with exceptional surface quality. The SLA process involves the use of a liquid photopolymer resin that solidifies when exposed to a UV laser, enabling the creation of precise and intricate structures (Fig. 3).

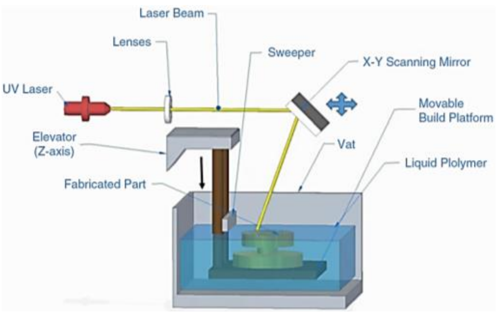


Fig. 3 Schematic of a stereolithography (SLA) process [20]

The SLA workflow begins with the generation of a 3D digital model using computer-aided design (CAD) software. This model is then processed through slicing software, which divides the design into thin cross-sectional layers and generates machine instructions. During printing, the SLA machine's build platform is submerged in a vat of liquid photopolymer resin. A UV laser, guided by the machine's instructions, selectively cures the resin to form the first layer of the object. Once cured, the build platform lowers incrementally, allowing the next layer to be cured atop the previous one. This process continues until the entire object is complete.

The underlying principle of SLA technology is photopolymerization, where liquid resin transitions into a solid polymer when exposed to light. This method provides SLA with its signature advantages: the ability to achieve fine details and smooth surface finishes. However, the liquid nature of the resin necessitates the inclusion of support structures to stabilize overhanging or intricate features during printing. These supports are removed during post-processing, which also typically involves further curing to ensure complete material stability.

SLA shares its foundation with similar technologies, including digital light processing (DLP) and continuous liquid interface production (CLIP). While SLA is the most widely adopted due to its versatility and accessibility, CLIP—a more recent innovation—offers a significant speed advantage, reportedly being up to 100 times faster than both SLA and DLP [21].

4.1 Materials used in SLA

A critical factor in the success of SLA for injection molding applications is the material properties of the resins used to produce the molds. SLA resins are photopolymers that cure into solid forms upon exposure to ultraviolet light. SLA employs a wide range of photopolymer resins, each engineered to meet the demands of specific applications. However, the inherent properties of SLA resins present unique challenges when used for injection molding tool inserts. Unlike traditional mold materials such as steel and aluminum, SLA resins typically exhibit lower mechanical strength and greater brittleness. These limitations restrict their suitability for high-stress or high-wear environments, which are common in injection molding processes. However, newly introduced engineering resins have greatly expanded their utility and are more successfully in bridging the gap for industrial use.

Heat Deflection Temperature (HDT) and mechanical strength are some of the key parameters that make a resin suitable for injection molding applications. In Table 1, there is review of the commercially available engineering-grade SLA resin types.

Table 1 - *General summary of commercially available SLA resin types*

Resin Type	Key Characteristics	Heat Deflection Temperature (HDT)	Mechanical Strength	Applications
Standard Resins	High resolution, smooth finish, low durability	~50°C	Low	Prototyping, low-stress molds
Tough Resins	Impact resistant, ABS-like properties	~70°C	Moderate	Low-pressure, small-batch molds
High-Temperature Resins	Excellent thermal stability	Up to 200°C	Moderate to High	Molds for higher-temperature thermoplastics
Rigid Resins	High stiffness, dimensionally stable, smooth surfaces	~100°C	High	Precision molds with tight tolerances
Flexible Resins	Elastomeric, low stiffness	~50°C	Low	Molds for flexible thermoplastics
Durable Resins	High elongation, low friction, resistant to wear	~80°C	Moderate	High-wear, low-pressure molds
Composite Resins	Reinforced with fibers, excellent thermal/mechanical properties	Up to 250°C	High	Demanding applications, high-strength molds

A critical requirement for injection molding tool inserts is *thermal stability*. During the molding process, inserts are exposed to elevated temperatures as molten materials are injected into the mold cavity. While metals like steel and aluminum demonstrate excellent resistance to these thermal loads, many SLA photopolymer resins have relatively low heat deflection temperatures. This makes them prone to deformation or degradation under high-temperature conditions, directly impacting their performance and longevity.

Durability also poses a significant challenge for SLA-produced mold inserts. Traditional mold materials are capable of withstanding extensive wear and maintaining dimensional accuracy over prolonged production runs. In contrast, SLA photopolymer resins tend to wear out more quickly, especially in high-volume production settings. This accelerated wear can compromise surface finish quality and dimensional precision, requiring more frequent replacement or maintenance of the tool inserts.

In response to these challenges, recent advancements in SLA materials have yielded high-performance resins with improved properties. These innovative materials offer enhanced mechanical strength, greater flexibility, and increased thermal stability, making them more viable for demanding mold insert applications ([15], [22], [23]). The optimal SLA resin for injection molding tool inserts must exhibit a balanced combination of strength, stiffness, and thermal resistance. Adequate strength ensures the mold can withstand clamping forces and injection pressures without fracturing. High stiffness enables the insert to maintain its geometric integrity under stress, ensuring consistent and precise part production, while improved thermal resistance enhances performance under high-temperature conditions.

4.2 Design recommendations for SLA inserts

The integration of SLA inserts into injection molding technology has proven most effective when paired with a universal metal base to house the core and cavity inserts. This modular approach offers significant benefits by enabling the use of a single master base to accommodate multiple insert designs. This strategy minimizes the size of SLA inserts required, reducing both production time and material consumption (Fig. 4). Additionally, the robust metal base provides essential structural support to the SLA inserts, particularly under the high pressures generated during the injection process.

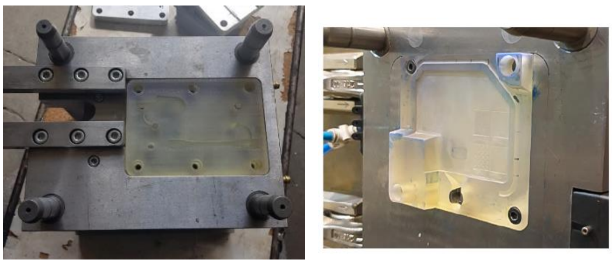


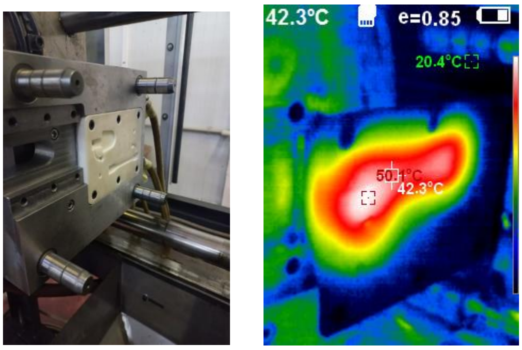
Fig. 4 Schematic of a stereolithography (SLA) process [24], [5]

To maximize the effectiveness of SLA inserts, the geometry of the mold should be slightly adjusted to accommodate the distinct mechanical, thermal, and dimensional properties of SLA materials. These adjustments ensure better alignment between the SLA inserts and the operational requirements of the injection molding process. Table 2 provides specific recommendations for key mold features, such as draft angles, wall thickness, and tolerances, tailored to the properties of SLA-produced inserts.

Table 2 - *General design guidelines for an SLA molding insert*

Draft angle	Radii	Gate size	Runner size	Holes (for sprue, ejectors etc.)	Cooling channels
Increase as much as possible	Increase as much as possible	increase by 2-3x	standard sizing recommendations apply	undersize by 0,2-0,3 mm and ream to size	standard sizing recommendations apply

When using SLA inserts, standard processing parameters for industrial polymers remain applicable. However, it is generally advisable to operate at the lower end of the recommended ranges for injection pressure, mold temperature, and melt temperature. These reduced parameters help mitigate the mechanical and thermal limitations of SLA materials, reducing the risk of insert deformation or premature wear. Cooling times represent another critical consideration due to the lower thermal conductivity of SLA inserts compared to traditional metal molds. The slower dissipation of heat necessitates longer cooling cycles to ensure proper solidification of the molded part. To optimize the process, insert temperature should be closely monitored and controlled until an acceptable cycle time is achieved (Fig. 5). This can be achieved through active temperature regulation systems, which help maintain consistent performance and dimensional accuracy over multiple production cycles.



a) b)

Fig. 5 Temperature control of the stereolithographic inserts; a) the molding insert placed in the master housing; b) thermographic camera image of the insert with temperature distribution after injection [24])

3. ADVANTAGES OF SLA MOLD INSERTS

SLA offers an innovative alternative to traditional machining methods for creating injection molds, particularly in prototyping scenarios for end-use plastic components. This approach is particularly advantageous during the pre-production phase, enabling manufacturers to test and refine designs before committing to the expense and time required for full-scale production tooling. SLA is best suited for use with thermoplastics that exhibit moderate melting points (below 300°C) and good flowability, making it compatible with a variety of materials, 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.

The technology excels in small production runs, typically ranging from 5 to 100 molded parts, and is most effective for small to medium-sized components with a volume of up to approximately 150 cm³. These runs can be performed using injection molding machines with clamping forces ranging from 50 to 80 tons. SLA is particularly advantageous for applications requiring the production of functional prototypes to evaluate design integrity and functionality before transitioning to large-scale manufacturing.

One of the key advantages of using SLA for mold prototyping is the dramatic reduction in lead time, with savings averaging between 50% and 90% compared to traditional tooling methods. Cost savings are equally significant, typically ranging from 50% to 70% ([5], [25], [26]). The SLA process also supports functional evaluation by enabling the use of production-grade thermoplastics, ensuring the molded parts meet application-specific material requirements.

The efficiency of SLA lies in its streamlined tool-making process, which involves fewer steps and requires minimal manual intervention. This allows for quicker iterations and adjustments to tool design, enabling early confirmation of part performance and suitability. Additionally, SLA facilitates the validation of thermoplastic material choices, ensuring the selected materials align with the mechanical, thermal, and dimensional demands of the application.

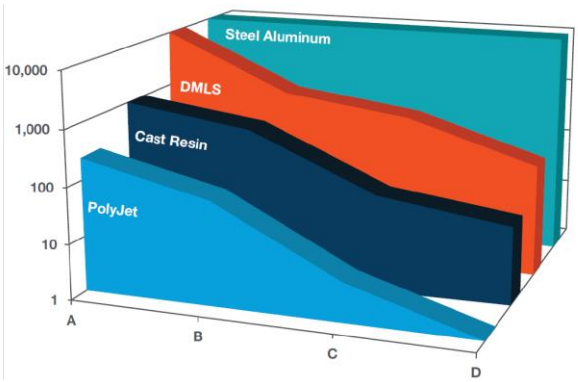
4. LIMITATIONS AND CHALLENGES OF SLA MOLD INSERTS

The performance and longevity of SLA molds in injection molding are influenced by several factors, particularly the type of thermoplastic material used during the process. Key characteristics of the plastic, such as melt temperature, viscosity, and abrasiveness, play critical roles. Higher melt temperatures and increased abrasiveness can accelerate wear on SLA molds, while high-viscosity polymers may lead to issues like short shots and weld lines. Although increased injection pressure can address these issues, SLA molds have limited strength and cannot tolerate the extreme pressures that are feasible with metal molds. Consequently, it is recommended to use thermoplastics with good flow characteristics to ensure smoother operations and prolonged mold life.

The geometry of the molded part also significantly impacts material selection and mold performance. Parts with simple, unobstructed designs allow for the use of higher-viscosity and higher-temperature polymers, while complex geometries may necessitate materials with superior flowability. As shown in Fig. 6, the lifespan of SLA molds can vary widely, ranging from as few as five cycles to over

1,000 cycles, depending on the material used and the operating conditions [28].

The thermal properties of SLA molds, driven by the inherent characteristics of photopolymers, necessitate lower injection speeds, pressures, and temperatures compared to metal molds. This results in a delayed cooling effect, which can influence the morphology, crystallinity, shrinkage, and mechanical properties of the molded parts [29], [30], [31]. SLA molds typically have lower heat conductivity, leading to longer cycle times, which help prevent part sticking but may slow overall production. Controlled cooling and ejection conditions, including the use of mold release agents, can further optimize part release and reduce the risk of tool damage ([32], [33]).



Material class	Polymer
A	PE, PP, PS, ABS, TPE
B	PP+G, PA, POM, PC+ABS
C	PA+G, PC, POM+G
D	PC+G, PPO, PPS

Fig. 6 Estimated number of parts obtained per tool, based on the polymer material used (Source: [27])

Part ejection poses its own set of challenges for SLA molds. For this reason, various studies and models have been developed to address the issues during part ejection and predict the mold behavior ([11], [12], [16], [33], [34]). The surface properties of photopolymer resins can result in stronger adhesion between the part and the mold, increasing the risk of damage during ejection. The use of mold release agents and design modifications, such as increasing draft angles, can facilitate easier part removal. Allowing adequate cooling time before ejection also minimizes the risk of damage to the mold and the part.

While SLA molds may not inherently achieve the dimensional precision of metal-machined tools, post-processing techniques such as sanding or machining can significantly improve size accuracy and reduce dimensional variations. Research indicates that parts produced using SLA molds are within acceptable tolerances for most applications, with over 80% of dimensions meeting specified tolerance ranges ([5], [36]). These findings underscore the viability of SLA molds for producing functional prototypes and small production runs, particularly when minor post-processing adjustments are feasible.

5. CONCLUSION AND FUTURE PROSPECTS

Stereolithography (SLA) has emerged as a transformative technology in additive manufacturing, particularly in the production of injection molding tool inserts. Its ability to significantly reduce lead times and production costs makes it a compelling choice for small production runs and rapid prototyping. SLA's capacity to create high-precision, intricate molds offers unparalleled design flexibility, enabling manufacturers to rapidly iterate and refine products before full-scale production.

However, SLA is not without its limitations. The mechanical and thermal properties of SLA-produced photopolymer resins remain a challenge when compared to traditional materials like steel or aluminum. The lower mechanical strength and higher brittleness of these resins restrict their use in high-stress or high-volume applications, where durability and resistance to thermal loads are critical. Furthermore, SLA molds require longer cooling times due to their lower thermal conductivity, which can impact cycle time efficiency.

Despite these challenges, SLA's advantages in cost reduction, time efficiency, and design adaptability cannot be overstated. Modular tooling systems, where SLA inserts are combined with robust metal bases, have addressed some of these limitations by improving structural stability and optimizing resource use. Advances in SLA material development are also addressing traditional constraints, with high-performance resins now offering improved strength, flexibility, and thermal stability. These developments are expanding the applicability of SLA to include more demanding injection molding scenarios.

Research shows that SLA is especially effective for prototyping end-use plastics and for producing functional molds in small to medium-scale production. By facilitating early validation of designs, thermoplastic selection, and mold performance, SLA enables manufacturers to mitigate risks and streamline product development processes. Additionally, post-processing techniques, such as sanding or machining, can further enhance dimensional accuracy and surface quality, ensuring that SLA-produced parts meet stringent tolerance requirements.

In conclusion, SLA is poised to revolutionize mold manufacturing, particularly in rapid tooling and low-volume production. As advancements in materials and processing technologies continue to improve the mechanical and thermal capabilities of SLA molds, the technology is expected to play a pivotal role in the future of injection molding. By combining speed, cost-efficiency, and design flexibility, SLA is building its position as a key technology for the future of mold manufacturing.

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NOTE

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