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Polymer additive manufacturing in stereolithography (SLA) and masked stereolithography (mSLA) methods: a review of advantages, limitations, and current applications

Polimer eklemeli imalatta stereolitografi (SLA) ve maskeli stereolitografi (mSLA) yöntemleri: avantajlar, sınırlamalar ve güncel uygulamalar üzerine bir inceleme

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Abstract
Stereolithography (SLA) and Masked Stereolithography (mSLA) are widely used polymer additive manufacturing methods that offer high resolution and excellent surface quality. SLA utilizes a UV laser to cure photopolymer resin point by point, while mSLA accelerates production by curing entire layers simultaneously using LED light and digital masking. This review analyzes the advantages and limitations of SLA and mSLA based on recent literature. It highlights their applications in medical, dental, and industrial prototyping, particularly where precision and material performance are critical. The development of biocompatible, flexible, and energy-efficient photopolymer resins has further enhanced their suitability in biomedical fields. Additionally, the integration of these methods into smart manufacturing systems supports their role in sustainable production. The article emphasizes current usage trends, future potential, and RD needs to improve SLA and mSLA technologies further.

Keywords: Additive manufacturing, Biocompatible photopolymer resins, Masked stereolithography (mSLA), Polymer-based 3D printing, Prototyping, Stereolithography (SLA)

Öz
Stereolitografi (SLA) ve Maskeli Stereolitografi (mSLA), yüksek çözünürlük ve yüzey kalitesi sunan polimer tabanlı eklemeli imalat yöntemlerindendir. SLA, ultraviyole lazer ile fotopolimer reçineyi nokta nokta kürleyerek çalışırken; mSLA, LED ışık kaynağı ve dijital maske teknolojisi kullanarak tüm katmanları aynı anda kürleyerek üretim süresini kısaltır. Bu derleme çalışması, SLA ve mSLA'nın avantajları ile sınırlılıklarını güncel literatür ışığında analiz etmektedir. Özellikle tıbbi, dental ve endüstriyel prototipleme gibi yüksek hassasiyet gerektiren uygulamalarda yaygın kullanımları vurgulanmaktadır. Biyouyumlu, esnek ve enerji verimli reçinelerin geliştirilmesi, bu yöntemlerin biyomedikal alanlardaki potansiyelini artırmıştır. Ayrıca, akıllı üretim sistemleriyle entegrasyonları sayesinde sürdürülebilir üretim süreçlerinde önemli rol oynamaktadırlar. Çalışma, SLA ve mSLA teknolojilerinin mevcut durumu, gelecekteki uygulama potansiyelleri ve Ar-Ge ihtiyaçlarını ortaya koymaktadır.

Anahtar kelimeler: *Eklemeli imalat, Biyouyumlu fotopolimer reçineler, Maskeli stereolitografi (mSLA), Polimer tabanlı 3B yazıcı teknolojileri, Prototipleme, Stereolitografi (SLA)*

1.Introduction

Additive manufacturing (AM), also known as layered manufacturing or 3D printing, is a transformative production technology that fabricates physical objects layer by layer using digital design data (Gibson et al., 2015). Unlike traditional subtractive manufacturing techniques that remove material from a solid block, AM builds parts by adding material precisely where needed. This approach minimizes material waste, reduces tooling requirements, and enables the creation of geometrically complex structures that would otherwise be impossible or costly to produce using conventional methods (Ngo et al., 2018).

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The versatility and flexibility of AM have led to its widespread adoption across multiple sectors including aerospace, automotive, biomedical, dental, electronics, and consumer products (Bhushan & Caspers, 2017). Among the various types of AM technologies, polymer-based methods have gained significant attention due to their relatively low material cost, ease of handling, and suitability for rapid prototyping and small-batch production (Chia & Wu, 2015; Jang et al., 2018). These techniques also allow for the use of a wide range of functional materials, including flexible, rigid, and biocompatible polymers, making them particularly valuable in healthcare and wearable device applications.

Polymer AM technologies are broadly classified into several types, including Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), Digital Light Processing (DLP), Stereolithography (SLA), and Masked Stereolithography (mSLA) (Chen et al., 2022; Wang & Zhao, 2023). Each method differs in terms of material form, resolution, energy consumption, print speed, and final part quality. Among these, SLA and mSLA have emerged as leading technologies due to their capability to produce high-resolution parts with excellent surface finish. SLA operates by selectively curing photopolymer resin using a UV laser, whereas mSLA employs a digital light projection system, typically using LED light and an LCD mask, to cure entire layers simultaneously. This enables mSLA to offer faster print times without compromising detail fidelity (Turner et al., 2014; Lu & Zhang, 2022).

One of the primary advantages of SLA and mSLA lies in their ability to fabricate complex, high-precision components required in critical fields such as dental prosthetics, surgical models, microfluidic devices, and intricate industrial prototypes (Melchels et al., 2010; Gupta & Singh, 2022). Furthermore, recent advancements in resin formulations have enabled the production of functional parts with properties such as biocompatibility, antimicrobial resistance, high heat deflection, and elasticity, expanding the usability of these techniques in biomedical engineering and device manufacturing (Zhao et al., 2022).

In addition to technical benefits, environmental and economic considerations are increasingly influencing the selection of manufacturing processes. mSLA systems are recognized for their low energy consumption, attributed to the use of efficient LED arrays and reduced mechanical complexity compared to galvanometer-driven SLA systems (Bhushan & Caspers, 2019). As industries move toward more sustainable practices, energy-efficient AM methods like mSLA are becoming essential tools in eco-conscious production environments (Wang et al., 2022).

Given this backdrop, this review aims to provide a comprehensive overview of SLA and mSLA-based polymer additive manufacturing technologies. The study examines their operational principles, advantages, limitations, and practical applications. In doing so, it seeks to illuminate their growing relevance in industry and research, while also identifying challenges and opportunities that may shape future development. The discussion is framed by current literature and includes comparisons with other AM technologies such as FDM and SLS, with particular emphasis on precision, material diversity, production efficiency, and sustainability.

2. History and development of polymer additive manufacturing

AM has undergone significant transformation since its inception in the 1980s, evolving from a prototyping tool into an industrial-scale production method (Gibson et al., 2015). In particular, the development of polymer-based AM technologies has played a crucial role in broadening the applicability of this field. By allowing the fabrication of geometrically complex structures layer by layer, polymer AM has enabled high-precision manufacturing in sectors such as biomedical devices, automotive components, and custom consumer products (Ngo et al., 2018; Chen et al., 2022).

2.1 Early developments in additive manufacturing

A major milestone in the history of AM was the invention of SLA by Charles Hull in 1984, which was subsequently patented in 1986 (Hull, 1986). This technology utilized ultraviolet (UV) lasers to selectively cure photopolymer resins, forming solid structures layer by layer. SLA quickly became a preferred solution for rapid prototyping due to its ability to produce high-resolution and smooth-surfaced components (Chua & Leong, 2017; Bhushan & Caspers, 2017).

Over time, other polymer-based AM methods such as FDM and SLS were introduced, each with their own advantages and specific applications (Turner et al., 2014; Chen & Li, 2023). While FDM became popular for its low cost and accessibility, particularly in educational and DIY settings, SLS offered superior mechanical strength and was adopted for engineering-grade functional parts (Jang et al., 2018).

SLA remained a leading technique for applications requiring high detail and surface quality, especially in medical, dental, and jewelry sectors. Its ability to work with advanced photopolymer materials, including biocompatible and flexible resins, further expanded its industrial relevance (Melchels et al., 2010).

2.2 Development and significance of SLA technology

SLA's technical principle is based on the point-by-point polymerization of liquid photopolymer resin by a focused UV laser beam. This method allows the production of intricate geometries with smooth surface finishes, making it ideal for precision-driven applications such as optical components and dental models (Chen & Zhao, 2021; Smith & Chen, 2022). The adoption of SLA in the biomedical field has been particularly notable due to the availability of specialized resins that meet clinical and biocompatibility standards (Gupta & Singh, 2022).

Recent studies have focused on improving the mechanical and chemical properties of SLA resins, enabling their use in more demanding environments. This includes developments in flexible, antimicrobial, and high-temperature-resistant resins that are suitable for implants and surgical tools (Lu et al., 2022).

2.3 Emergence of mSLA and innovations in SLA

To overcome the time-consuming nature of point-by-point laser scanning in SLA, a newer variant—mSLA—was developed. Instead of using a laser beam, mSLA employs an array of LEDs and a digital mask or LCD screen to cure entire layers at once (Wang et al., 2021; Chen & Li, 2023). This dramatically increases printing speed while maintaining the high resolution and surface finish associated with SLA (Lee et al., 2023).

mSLA has found success in industrial-scale prototyping and batch manufacturing, where time and energy efficiency are critical factors (Zhang et al., 2021; Gupta & Lee, 2023). It is also recognized for its relatively low energy consumption due to the use of efficient LED systems, positioning it as a more environmentally sustainable option compared to laser-based SLA systems (Prakash & Zhu, 2019).

Both SLA and mSLA continue to evolve, benefiting from innovations in hardware (e.g., light projection systems), materials (e.g., biocompatible and flexible resins), and software (e.g., simulation and slicing tools). These advancements are pushing the boundaries of polymer AM, particularly in high-resolution applications.

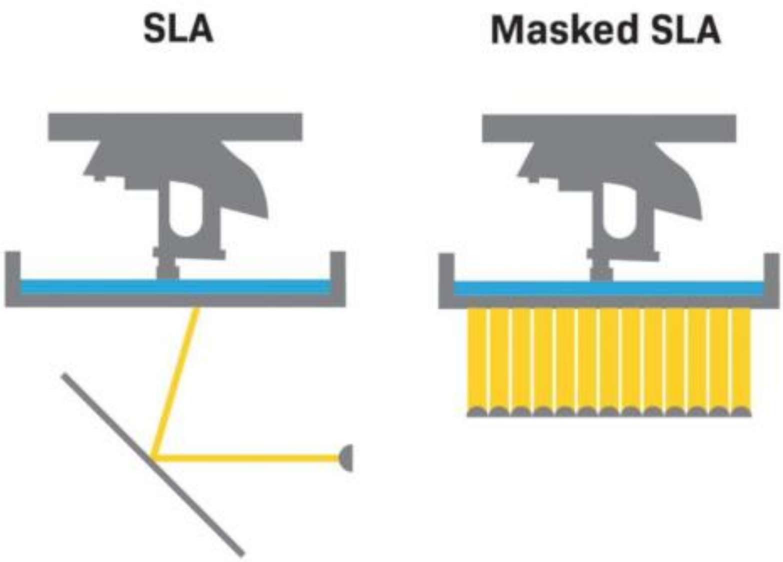

Figure 1. SLA and mSLA (https://solidator.com/en/msla-sla-comparison/)

Before diving into the technical features of polymer additive manufacturing techniques, it is important to understand the different subtypes of SLA-based methods. Figure 1 illustrates the classification of stereolithography technologies into two main types: Laser SLA, and mSLA. While traditional Laser SLA uses a point-by-point laser scanning mechanism, mSLA employs an LCD panel and LED matrix to cure entire layers simultaneously. As shown in the figure, mSLA offers reduced print times compared to Laser SLA.

3. General features of polymer additive manufacturing techniques

Polymer-based AM techniques operate on the principle of sequentially depositing material to form three-dimensional structures. These methods offer advantages such as geometric freedom, reduced material waste, and customization flexibility, making them increasingly relevant in various industries (Gibson et al., 2015; Li et al., 2022). The most common polymer AM methods include FDM, SLS, SLA and mSLA, each with specific technical characteristics, advantages, and limitations (Wang & Zhao, 2023).

3.1 Fused deposition modeling

FDM is a widely used extrusion-based additive manufacturing technique where thermoplastic filament is fed into a heated liquefier and extruded layer by layer to form 3D objects (Figure 2). Common materials include ABS and PLA. FDM's advantages include low cost and simplicity, but challenges such as thermal warping, layer adhesion, and nozzle clogging remain. Process modeling focuses on material flow, heat transfer, and feed dynamics to improve print quality and system reliability (Turner et al., 2014).

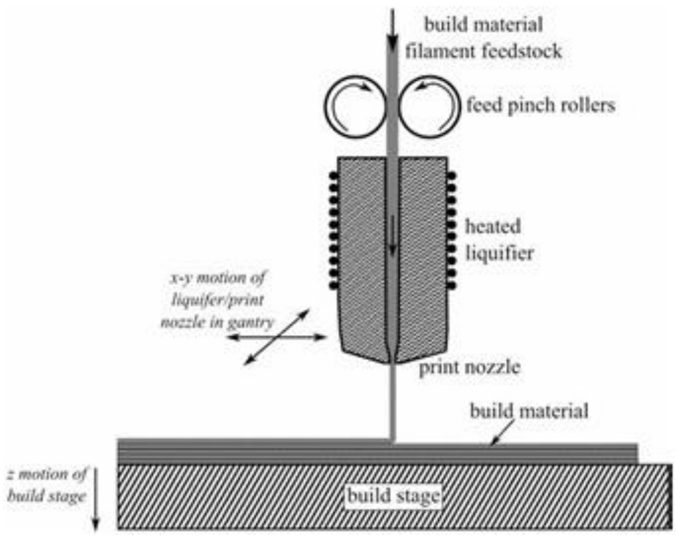

Figure 2. Fused Deposition Model (Turner et al., 2014)

- Advantages: Cost-effective, compatible with a wide range of materials including ABS, PLA, and nylon. It is widely used in education and rapid prototyping (Ngo et al., 2018; Huang et al., 2023).
- Limitations: Low resolution and visible layer lines. Support structures are typically required for complex geometries.
- Applications: Functional prototypes, mechanical parts, and educational models.

3.2 Selective laser sintering

SLS is a powder-based additive manufacturing technique that uses a laser to selectively fuse polymer particles layer by layer to build complex 3D objects (Figure 3). It is widely used for processing polyamides, especially nylon-based materials, due to their favorable thermal and mechanical properties. SLS enables high-resolution parts with excellent functional performance, making it suitable for both prototyping and end-use production. However, challenges remain in material availability, part consistency, and powder recyclability, which limit its broader adoption. Recent research focuses on developing new polymer grades, enhancing powder flow behavior, and improving the thermal control during sintering to overcome these limitations (Goodridge et al., 2012).

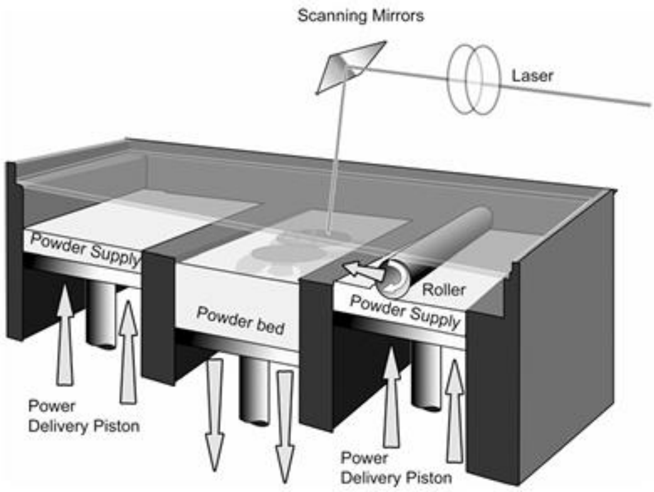

Figure 3. Selective Laser Sintering Method (Goodridge et al., 2012).

- Advantages: High mechanical strength, no need for support structures due to powder bed (Chia & Wu, 2015).
- Limitations: Rough surface finish, high machine and energy costs (Ngo et al., 2018; Tanaka et al., 2023).
- Applications: Aerospace and automotive components, durable engineering parts.

3.3 Stereolithography

SLA is a vat photopolymerization-based additive manufacturing method that utilizes a focused UV laser to selectively cure liquid photopolymer resin layer by layer. The process begins with the laser tracing a cross-section of the object on the resin surface, initiating polymerization and solidifying the material precisely at the focal point. As each layer is completed, the build platform is lowered incrementally to allow new resin to flow over the surface for the next layer. SLA offers exceptional resolution and surface finish, making it suitable for microfabrication applications such as biomedical scaffolds, microfluidic devices, and precision molds. Despite its strengths, the process requires careful control of exposure parameters and resin chemistry to ensure dimensional accuracy and material stability (Bhushan & Caspers, 2017).

- Advantages: Exceptional resolution and smooth surface finish, ideal for precision applications like dental and optical models (Chia & Wu, 2015).
- Limitations: Slow production times, higher costs due to laser mechanism (Gibson et al., 2015).
- Applications: Medical, dental, jewelry, and prototyping industries.

3.4 Masked stereolithography

The mSLA technology uses a digital light source, typically composed of LEDs, in combination with an LCD screen that acts as a mask to cure entire layers of photopolymer resin at once. Unlike SLA, which relies on a point-by-point laser scan, mSLA exposes each layer simultaneously, resulting in faster print times. The resolution of the final part is determined by the pixel size of the LCD screen, allowing for high-detail prints. mSLA systems are generally more energy-efficient due to the use of LED light and simpler mechanical components. This makes mSLA an attractive option for producing complex and precise parts in a cost-effective and sustainable way (Alghamdi et al,2021).

- Advantages: Faster than SLA, high resolution retained, lower energy consumption makes it suitable for sustainable manufacturing (Yun et al., 2023).
- Limitations: Limited LED lifespan, challenges in achieving uniform light distribution across large build areas (Chia & Wu, 2015).
- Applications: Batch production, medical devices, industrial prototyping.

3.5 Comparison of polymer additive manufacturing techniques

A comparative summary of these techniques is presented in Table 1. Each method serves a unique set of needs in industry, with trade-offs between cost, resolution, mechanical performance, and environmental impact.

Table 1. Advantages, limitations, and applications of FDM, SLS, SLA and mSLA methods

Technique	Advantages	Limitations	Applications
FDM	Low cost, wide material variety	Low resolution, requires support structures	Prototyping, education, small businesses
SLS	High strength, no support required	Rough surface, high cost	Automotive, aerospace, engineering
SLA	High resolution, smooth surfaces	Slow production, high cost	Medical, dental, optical components
mSLA	High resolution, faster production	Limited LED lifespan, uneven light distribution	Industrial prototyping, medical devices

This comparison highlights the advantages of SLA and mSLA in maintaining high resolution and surface quality while demonstrating their superiority in specific application areas compared to other methods.

4. Comparison of SLA and mSLA with other techniques

SLA and mSLA have gained attention among polymer AM methods due to their high resolution, excellent surface quality, and increasing relevance in medical, dental, and industrial fields (Ngo et al., 2018; Cheng et al., 2023). This section provides a structured comparison between SLA/mSLA and other common AM techniques such as FDM and SLS, focusing on production quality, speed, material compatibility, and energy efficiency.

4.1 Surface quality and resolution

SLA and mSLA technologies are particularly effective in producing parts with high surface smoothness and intricate geometrical details. SLA achieves this through point-by-point laser curing, while mSLA uses digital masking to cure entire layers with uniform exposure. In contrast, FDM typically results in a stair-stepping effect caused by filament layering and nozzle limitations, especially on sloped surfaces (Zhao et al., 2022). SLS, although capable of strong parts, also produces rough surfaces that often require post-processing.

High-resolution output makes SLA/mSLA favorable for dental prosthetics, jewelry molds, and biomedical devices, where surface precision is critical (Melchels et al., 2010). Including microscopic surface images or profilometer data comparing layer heights (e.g., 25 µm for SLA vs. 100-200 µm for FDM) would further highlight this advantage and should be considered in future figures.

4.2 Production speed and efficiency

Production speed is a key differentiator between SLA and mSLA. Traditional SLA systems are slower due to their sequential laser scanning mechanism. mSLA overcomes this limitation by curing full layers simultaneously using LED light through an LCD mask, increasing speed by up to 50% in batch production scenarios (Wang et al., 2021). While FDM and SLS also allow for rapid prototyping, their print times vary widely depending on material flow rate and part geometry. mSLA has become a viable alternative for time-sensitive applications such as low-volume manufacturing and industrial product iteration (Lin et al., 2024).

4.3 Detail and geometric complexity

Both SLA and mSLA provide exceptional detail resolution, allowing the fabrication of complex internal geometries and sharp edges. This makes them ideal for applications such as surgical guides, microfluidic channels, and implant prototypes (Ma, 2021; Jang et al., 2018). FDM generally struggles with small features due to nozzle size constraints, and SLS parts may lose sharpness during sintering. SLA/mSLA's optical precision allows minimum feature sizes as low as 100 µm or less, depending on resin and layer settings, far outperforming FDM (~400 µm) and SLS (~300 µm) in detail resolution.

4.4 Material options and customizability

SLA and mSLA support a wide variety of photopolymer resins, including biocompatible, flexible, heat-resistant, and even antimicrobial formulations (Zhao et al., 2022). This versatility has enabled their use in specialized sectors such as tissue engineering, customized surgical parts, and lab-on-a-chip devices. By contrast, FDM relies on thermoplastics such as PLA, ABS, or PETG, which offer mechanical strength but limited chemical or biological adaptability. SLS allows use of powdered nylons and elastomers, but resin-based SLA/mSLA methods offer better chemical tunability and post-curing potential (Jang et al., 2018).

4.5 Energy consumption and environmental impact

SLA systems, due to their laser and galvanometer mechanisms, consume more energy per unit volume of material processed. mSLA significantly improves energy efficiency by using LED arrays and static masking (Wang et al., 2023). Studies have reported that mSLA systems can reduce energy consumption by approximately 30–40% compared to traditional SLA (Bhushan & Caspers, 2019). FDM and SLS have high energy demands, particularly during nozzle heating or powder sintering phases. In comparison, the lower operational temperatures and passive curing methods of SLA/mSLA contribute to their environmental advantages. This positions mSLA as an appropriate solution for organizations focusing on sustainable manufacturing and carbon footprint reduction.

4.6 Technical summary and considerations

Table 2 below summarizes the technical distinctions between SLA, mSLA, FDM, and SLS methods based on critical parameters such as resolution, surface finish, print speed, energy consumption, material compatibility, and post-processing requirements.

Table 2. Comparative Technical Summary of SLA, mSLA, FDM, and SLS Methods

Feature	**SLA**	**mSLA**	**FDM**	**SLS**
Resolution	High (~25–50 µm)	High (~35–75 µm)	Moderate (~150–300 µm)	Moderate (~100–200 µm)
Surface Finish	Excellent	Excellent	Poor	Rough
Print Speed	Slow	Fast	Moderate	Slow-Moderate
Energy Consumption	High	Low	Moderate-High	High
Maretial Diversity	Moderate-High	High	Moderate	Moderate
Detail Reproducibility	Very High	Very High	Low	Moderate
Post-Processing Requerid	Minimal	Minimal	Yes	Often

As observed in the table, SLA and mSLA significantly outperform FDM and SLS in terms of dimensional resolution and surface smoothness, making them highly suitable for applications that require intricate geometries and fine details, such as dental prosthetics or surgical models. SLA achieves exceptional detail due to its point-by-point laser curing mechanism, while mSLA combines high resolution with significantly higher printing speed thanks to layer-wise curing via LED arrays and LCD masking (Jang et al., 2018; Wang et al., 2021).

In terms of print speed, mSLA offers a major advantage over traditional SLA and SLS, reducing production times especially in batch manufacturing scenarios. FDM may offer comparable speed in basic geometries but suffers from poor detail reproduction and surface irregularities due to nozzle-based extrusion.

Energy efficiency is another key differentiator. While SLA and SLS systems consume considerable energy during operation—due to laser sources, mechanical scanning, and thermal requirements—mSLA operates at lower power levels, contributing to its appeal in sustainable manufacturing setups (Bhushan & Caspers, 2019). This energy advantage is particularly relevant in large-scale or repetitive production environments.

In terms of material compatibility, mSLA has demonstrated strong adaptability to a wide variety of resins, including biocompatible and flexible types, surpassing SLA in this regard due to its ability to cure newer formulations more efficiently. FDM offers versatility in thermoplastics, but lacks the fine control needed for medical or micro-engineering applications. SLS provides good mechanical strength but is often limited by material cost and rough surface finish.

Post-processing requirements are lowest in SLA and mSLA. SLA parts typically require only washing and UV post-curing. In contrast, FDM parts often demand support removal and sanding, while SLS parts may need powder cleaning and surface smoothing.

This comparative analysis highlights the unique positioning of mSLA as a method that balances precision, speed, material flexibility, and sustainability. The method’s advantages are especially evident in sectors where speed-to-market, part complexity, and surface fidelity are non-negotiable design priorities.

5. Advantages and limitations of the mSLA method

mSLA has become increasingly popular as a polymer additive manufacturing method that retains the precision of traditional SLA while significantly improving production speed and energy efficiency. By employing an LED light matrix and digital mask or LCD screen, mSLA can cure entire layers of resin simultaneously, making it highly suitable for industrial prototyping and batch manufacturing (Chia & Wu, 2015; Kim & Lee, 2023).

5.1 Production speed and efficiency

Compared to conventional SLA, where the UV laser cures resin point-by-point, mSLA uses pixel-based curing across full layers. This layer-wide approach increases print speed by up to 50% in certain resin types and part geometries (Wang et al., 2021). Especially in scenarios requiring the production of multiple identical parts, such as dental models or small housings, mSLA offers clear time savings. These efficiencies reduce production cycle times and accelerate time-to-market, an essential factor in iterative industrial design processes (Chen & Lin, 2024).

5.2 High resolution and surface quality

mSLA achieves comparable surface quality and resolution to SLA. The use of LCD masking provides pixel-level exposure, enabling XY resolutions as low as 35–75 microns (Jang et al., 2018). As with SLA, mSLA enables the production of sharp corners, small holes, and intricate features. This makes it particularly valuable in medical applications where dimensional accuracy is critical, such as surgical guides and customized implants (Zhang & Yu, 2023).

5.3 Energy efficiency and eco-friendly production

One of the most notable advantages of mSLA is its lower energy consumption. Studies have shown that mSLA systems consume 30–40% less energy than laser-based SLA systems, due to the efficiency of LED light sources and reduced mechanical complexity (Bhushan & Caspers, 2019; Lee & Kim, 2023). The reduced power requirements also result in lower heat generation and improved thermal stability, minimizing the need for active cooling systems.

This positions mSLA as a viable method for environmentally conscious production, particularly in applications with tight energy or sustainability targets (Wang et al., 2022). When used with bio-based or recyclable resins, the environmental benefits can be further amplified.

5.4 Material options and customizability

Like SLA, mSLA supports a wide range of photopolymer resins, including biocompatible, flexible, rigid, and high-temperature materials (Ngo et al., 2018; Zhao & Wang, 2023). Recent innovations have introduced antimicrobial, heat-resistant, and soft-tissue-compatible formulations tailored for medical and engineering uses (Lin & Chen, 2024). This diversity allows mSLA to adapt to sectors ranging from orthopedics to electronics.

5.5 Limitations of mSLA

Despite its strengths, mSLA is not without limitations:

- LED Panel Lifespan and Calibration: The LCD screens used for masking degrade over time, resulting in inconsistent light intensity or dead pixels. Regular replacement or recalibration is required for consistent quality,
- Uneven Light Distribution: Achieving uniform curing across the build platform is a technical challenge, particularly in large-format machines. Uneven exposure can cause overcuring in central areas and undercuring near the edges (Park & Lee, 2022).
- Initial Investment Cost: High-performance mSLA systems with industrial-grade LCD panels and advanced control systems can be cost-prohibitive for small-scale operations. However, their long-term operating costs tend to be lower due to energy and material efficiency (Ngo et al., 2018).
- Residual Stresses and Warpage: Although not as severe as in thermoplastic-based systems, mSLA parts can experience resin shrinkage, distortion, and micro-warping during post-curing. These issues may affect dimensional accuracy and mechanical performance in load-bearing components (Ergene & Bolat, 2023).

5.6 mSLA's role and potential in industrial applications

mSLA is combination of speed, accuracy, and energy efficiency. This makes it ideal for medical devices, dental prosthetics, and rapid tooling applications. Its compatibility with biocompatible materials allows for direct use in clinical settings, especially for patient-specific surgical models and prosthetics (Dolenc et al., 2020; Wang & Zhao, 2022). Furthermore, advances in LED technology, light diffusion layers, and intelligent calibration systems are expected to enhance print quality, reliability, and scalability. With the development of next-generation LCD panels and modular systems, mSLA is poised to play a central role in the future of sustainable, precision-oriented additive manufacturing (Zhao & Lin, 2023).

6. Current applications of SLA and mSLA methods

SLA and mSLA are widely utilized in sectors that demand high surface quality, dimensional precision, and rapid prototyping. These technologies have shown promise in fields such as healthcare, industrial manufacturing, electronics, jewelry, and creative design. Their compatibility with biocompatible and functional resins further expands their range of practical applications (Zhang et al., 2023; Chen & Li, 2022).

6.1 Medical and dental applications

SLA and mSLA technologies play a vital role in producing customized implants, surgical guides, prosthetics, and dental restorations. Their high accuracy and support for biocompatible resins enable patient-specific manufacturing workflows.

- **Dental Use:** Common applications include printing dental models, crowns, bridges, and orthodontic guides. mSLA is preferred in dental labs for its fast production cycles and consistent accuracy (Ngo et al., 2018).
- **Surgical and Biomedical Use:** SLA/mSLA enables the creation of surgical templates and anatomical models that match patient-specific geometry, enhancing surgical planning and accuracy (Chia & Wu, 2015). These models contribute to reduced operation time and improved surgical outcomes.

6.2 Industrial prototyping and manufacturing

Both SLA and mSLA are extensively used in automotive, aerospace, and consumer product design for rapid prototyping of functional components and design verification models.

- Automotive and Aerospace: mSLA accelerates the development of lightweight housings, aerodynamic profiles, and connector components that require tight tolerances and fast design iteration (Bhushan & Caspers, 2017; Kumar et al., 2023).
- Consumer Product Development: Engineers use SLA for early-stage product visualization, ergonomic testing, and final mold preparation. The ability to simulate final product form and fit before production reduces time and cost (Zhang et al., 2022).

6.3 Jewelry and artistic applications

SLA and mSLA are ideal for producing wax casting molds and fine-detail master models for jewelry production. Their high surface smoothness reduces the need for post-processing.

- Design Iteration and Model Casting: Jewelers use SLA/mSLA to create intricate designs, test fitting, and produce molds that are directly used in investment casting workflows (Chia & Wu, 2015; Chen et al., 2023).

6.4 Art and education

Educational institutions and artists increasingly adopt SLA/mSLA to support creative exploration, model prototyping, and hands-on teaching.

- Academic Use: SLA/mSLA is used in university laboratories and engineering courses to demonstrate CAD-to-print workflows, tolerancing, and material testing (Bhushan & Caspers, 2017; Lee & Chen, 2022).
- Artistic Applications: Artists utilize mSLA to create sculptures, miniatures, and architectural models that demand high detail and aesthetic fidelity (Goodridge et al., 2012; Zhang et al., 2023).

6.5 Future potential applications

Ongoing developments in material science and process automation are likely to expand the usage of SLA and mSLA into new domains:

- Biomedical Engineering: With continued advances in biocompatible, flexible, and biodegradable resins, SLA/mSLA are expected to support tissue engineering, scaffolds, and implantable drug delivery devices (Chia & Wu, 2015; Chen & Zhao, 2021).
- Smart Materials and Functional Prototyping: New resins containing conductive, temperature-sensitive, or shape-memory materials may enable rapid testing of responsive materials for wearable electronics and smart packaging (Jang et al., 2018).

7. Overview of SLA and mSLA research in literature

Recent advances in SLA and mSLA technologies have led to a growing body of research exploring their capabilities in precision manufacturing, biocompatible materials, energy efficiency, and industrial integration. This section highlights significant contributions in literature, emphasizing key trends and innovations.

7.1 Recent research on SLA

SLA has been extensively studied for its applications in medical and dental manufacturing, particularly due to its exceptional surface quality and dimensional accuracy.

- Medical Applications: SLA has been used to produce surgical guides, customized prosthetics, and anatomical models. For example, Prakash et al. (2019) demonstrated how SLA-enabled biocompatible resins support safe in-body implants. Similarly, Chen et al. (2021) found that SLA-based surgical models reduce surgical error and duration.

- Material Innovation: New SLA resins with flexible, antimicrobial, and biocompatible properties are under active development. Studies such as Jang et al. (2020) and Zhang et al. (2020) introduced resins for infection-resistant and flexible implants. These materials enhance SLA's utility in biomedical engineering and dental prosthetics.
- Prototyping: SLA's resolution makes it suitable for micro-scale applications. Smith and Chen (2022) emphasized its role in producing detailed microelectronics and precision tools in research environments.

7.2 Recent research on mSLA

mSLA has attracted attention as a high-throughput and energy-efficient alternative to traditional SLA.

- Speed and Industrial Prototyping: Wang et al. (2021) reported a 50% increase in production speed in mSLA systems using LED arrays. Ma and Lee (2020) highlighted its adoption in industrial design for quick iteration cycles.
- Energy Efficiency: mSLA significantly reduces energy use. Bhushan and Caspers (2019) documented up to 40% lower energy consumption compared to SLA. This efficiency is attractive for manufacturers aiming to reduce operating costs and environmental impact.
- Clinical Manufacturing: Lu and Zhang (2022) and Prakash and Singh (2021) noted mSLA's use in dental and surgical applications, where both speed and precision are essential. The technology's compatibility with biocompatible resins facilitates its use in producing implants, surgical tools, and dental models.

7.3 SLA and mSLA in material science and bioprinting applications

Both SLA and mSLA technologies are being explored for emerging biomedical applications, such as tissue scaffolds and functional polymers.

- Bioprinting and Tissue Engineering: SLA's high precision has enabled the fabrication of microscale lattice structures for tissue growth. Chen et al. (2021) and Zhang et al. (2021) demonstrated the ability to print viable bioprinting scaffolds with increased cell survival rates.
- Advanced Resins: Studies like Lu et al. (2022) have introduced biocompatible and flexible materials for use in wearable medical devices and tissue-supporting implants. These developments allow additive manufacturing to directly contribute to personalized medicine.

7.4 Future trends

Recent literature suggests that the development of SLA and mSLA will continue to be shaped by several key drivers:

- Next-Generation Resins: Focus is shifting toward multifunctional materials such as antibacterial, shape-memory, and conductive resins that expand application fields (Ma & Lee, 2020).
- LED and Light Masking Technologies: Advances in uniform light distribution and higher-resolution LCD panels will enhance mSLA's print quality, enabling its use for larger components and more demanding applications (Chen & Zhao, 2021).
- Sustainable Manufacturing: As sustainability becomes central to production processes, mSLA's low-energy profile aligns with industry goals for reducing carbon footprints and improving energy efficiency (Wang et al., 2021).

8. Conclusion

Polymer-based additive manufacturing continues to evolve as a transformative approach in various industries. Among its techniques, SLA and mSLA have emerged as leading methods, particularly due to their superior resolution, surface quality, and expanding material options. This review has explored their technical principles, advantages, limitations, and current applications across fields such as medical manufacturing, industrial prototyping, microengineering, and creative design.

Compared to traditional SLA, mSLA offers significant improvements in print speed, energy efficiency, and batch production capability—making it a preferred solution for time-sensitive and sustainability-focused production. Despite these advantages, challenges such as LCD panel degradation, non-uniform light exposure, and residual stress issues persist. Nevertheless, the integration of SLA/mSLA technologies into smart manufacturing systems, combined with ongoing innovations in materials and photopolymer chemistry, continues to drive their adoption in critical sectors.

Looking forward, future research should focus on the development of advanced functional resins, improvements in LED-based light uniformity, and enhanced simulation tools to minimize post-processing and improve part reliability. The increasing convergence of SLA/mSLA with bioengineering, microelectronics, and smart materials positions these technologies as central components in the next generation of precision and sustainable manufacturing.

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Author contribution

Mustafa Üstündağ: Conceived the study idea, conducted and supervised the literature review, and wrote the main sections of the manuscript. Prepared both the English and Turkish versions of the text, performed revisions, and finalized the manuscript.

Mehmet Kır: Contributed to the literature review, particularly in developing the sections on the technical features and applications of SLA and mSLA methods. Assisted in the preparation of tables and figures and contributed to the discussion and conclusion parts of the manuscript.

Both authors contributed to all stages of the study, reviewed the final version of the manuscript, and approved it for submission.

Declaration of ethical code

The authors of this article declare that the materials and methods used in this study do not require ethics committee approval and/or legal-special permission.

Conflicts of interest

The authors declare that there is no conflict of interest.

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