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PHOTOPOLYMERIZATION ADDITIVE MANUFACTURING FOR MICROMOLD APPLICATION: A SYSTEMATIC REVIEW

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Abstract:

Photopolymerization Additive Manufacturing (PAM) has emerged as a transformative technology for fabricating micromolds, offering exceptional precision in controlling micro-scale features critical for advanced manufacturing applications. Despite its potential, widespread adoption of PAM in micromolding is hindered by challenges related to material limitations, process optimization, scalability, and the integration of hybrid manufacturing approaches. This systematic literature review aims to provide a comprehensive assessment of PAM's current role in micromold applications, focusing on technological advancements, existing hurdles, and future research needs. A detailed review of peer-reviewed literature from leading databases, such as Scopus and Web of Science, was conducted, emphasizing studies published between 2022 and 2024. The review follows the PRISMA methodology, with a final selection of 28 primary studies. Three key themes were identified: (1) Vat Photopolymerization (VPP) techniques and materials, (2) applications and innovations in 3D printing, and (3) materials science and engineering in 3D printing. Notably, limitations in material diversity, difficulty in maintaining consistent layer resolution, and challenges in scaling up production remain significant barriers. The review also highlights the critical need for research into new photopolymer materials and hybrid manufacturing techniques that can enhance performance and scalability. Ultimately, addressing these issues is essential for PAM's broader industrial adoption, particularly in high-precision and high-performance manufacturing sectors.

Keywords:

Photopolymerization, Additive Manufacturing, Micromold

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Introduction

Photopolymerization Additive Manufacturing (PAM) is recognized as a revolutionary technique in microfabrication, particularly for micromold applications, due to its ability to produce intricate microstructures with high precision (K. Zhang et al., 2024). PAM utilizes light-induced polymerization to fabricate complex three-dimensional geometries layer by layer, making it a preferred method for creating high-resolution micro-scale features. This precision is critical for applications in advanced manufacturing, where micromolds are essential for producing small, complex components across industries such as microelectronics, biomedical devices, and precision engineering (Aabith et al., 2022; Knowles, 2000; Leary et al., 2017; Otero et al., 2016).

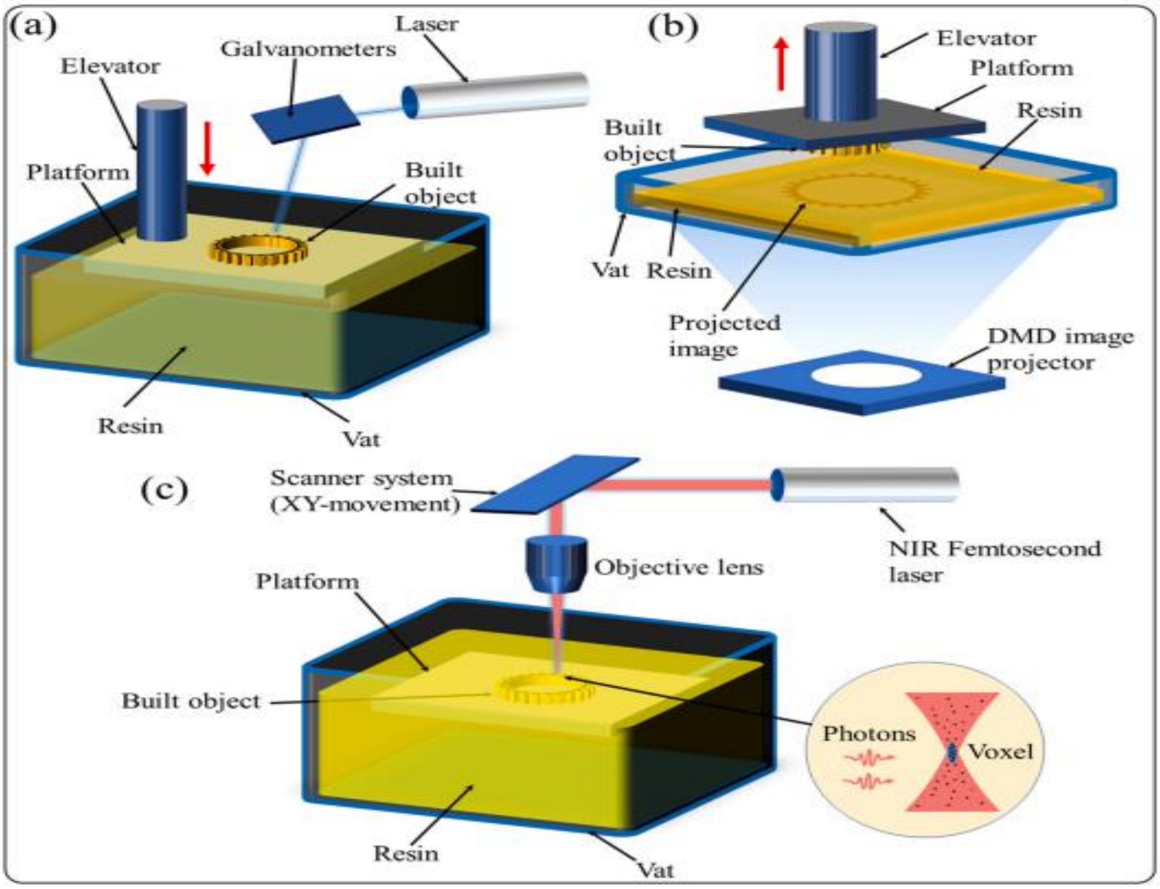

Figure 1. (a) Scheme Of Bottom-Up Mask Projection Stereolithography (MPSL). (b) Scheme Of The Traditional Laser-Based Stereolithography (SLA). (c) Scheme Of Two Photon Polymerization (TPP).

Source: Reproduced with permission from (F. Zhang et al., 2017).

Despite its promise, several challenges and issues hinder the broader adoption of PAM for micromolding applications. One of the key challenges is the limited diversity of photopolymer resins available for micromold fabrication. These resins must exhibit not only high mechanical strength but also exceptional thermal stability and chemical resistance to withstand the harsh conditions during the molding process. Current commercial resins often fall short in these areas, limiting their effectiveness in certain high-performance applications (Hegab et al., 2023; Mobarak et al., 2023). There is also a need for photopolymers that can balance rigidity and flexibility, as micromold materials require properties that can adapt to varying manufacturing conditions.

Another significant issue is the scalability of PAM for micromold production. While PAM excels at fabricating small components with high precision, scaling up the process to accommodate larger build volumes without compromising resolution and accuracy remains a technical hurdle. Uniform curing of the photopolymer resin across the entire build platform is difficult to achieve, often resulting in inconsistent layer thicknesses or defects in the final product (Cao et al., 2021). This inconsistency is particularly problematic in industries requiring flawless micro-scale features, such as micro-optics and precision instrumentation. Advances in light delivery systems, such as more sophisticated laser or projector-based curing methods, are required to mitigate these issues.

Material shrinkage during the curing process is another area of concern. Photopolymers tend to shrink as they cure, which can result in dimensional inaccuracies, especially in highly detailed structures (Jafari et al., 2021; Tang et al., 2022). This phenomenon complicates the production of micromolds that require strict tolerances, as the post-processing adjustments needed to correct dimensional errors can add complexity and cost to the manufacturing process. In addition to material and scalability challenges, there are issues related to process optimization. Achieving the optimal balance between layer thickness, curing time, and light intensity is critical for ensuring high-quality micromold production. Suboptimal settings can lead to incomplete curing, poor surface finishes, or mechanical weaknesses in the final product. Thus, process parameters must be carefully calibrated, often requiring significant trial and error, which can slow down the overall production cycle (Shaukat et al., 2022).

Moreover, the cost associated with PAM technology, including the photopolymers and high-precision equipment required, remains a barrier to its widespread industrial adoption. While PAM offers material efficiency by minimizing waste compared to subtractive techniques, the high upfront costs of implementing the technology can be prohibitive for smaller manufacturers or research institutions (Bean & Long, 2024; Kuenstler et al., 2023).

In conclusion, while PAM offers numerous advantages in terms of precision, flexibility, and material efficiency for micromold production, several critical issues need to be addressed. These include the development of more advanced photopolymer resins, improvements in process scalability and uniformity, and further optimization of curing processes. Addressing these challenges is essential for PAM to realize its full potential in high-performance manufacturing sectors and for its broader industrial adoption. With continued research and technological advancements, PAM holds the promise of revolutionizing micromold fabrication and enabling innovations across various high-tech industries.

Literature Review

Photopolymerization Additive Manufacturing (PAM) has significantly advanced micromold production, allowing for the creation of complex microstructures with high precision. However, despite these technological achievements, several challenges hinder the full potential of PAM, particularly concerning material properties, process optimization, and environmental sustainability. One of the most significant issues lies in the limited diversity and mechanical robustness of photopolymerizable resins used in Additive Manufacturing (AM). Specifically, materials that combine high mechanical strength, thermal stability, and chemical resistance remain scarce, presenting a barrier to broader industrial applications (Becker et al., 2024). The customization of photopolymer resins to meet specific functional requirements for micromolds has yet to reach its full potential, necessitating further research into material innovation.

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Moreover, achieving dimensional accuracy and uniform layer thickness across larger build volumes presents an ongoing challenge in PAM, as resin shrinkage during polymerization can result in inaccuracies (Feng et al., 2024). The formation deviations caused by ceramic slurries during the photopolymerization process highlight the necessity of developing new models and processes to mitigate such issues, particularly in ceramic-based micromolds. These deviations can compromise the quality of final products, especially in industries where precision is paramount. Process parameters such as curing time and light intensity must be optimized to minimize shrinkage and ensure uniform layer deposition.

Sustainability is another growing concern within the field of PAM. The development of biobased materials for photopolymerization, such as the use of δ-valerolactone, presents a promising solution to reducing the environmental impact of AM processes (Yue et al., 2024). However, the adoption of sustainable materials must be balanced with maintaining the mechanical properties required for high-performance micromolds. Additionally, environmental and safety risks associated with emissions from photopolymerization processes have been increasingly scrutinized, particularly concerning exposure to hazardous chemicals in 3D printing environments (Chuang et al., 2024). As PAM continues to evolve, there is an urgent need to address these health and environmental concerns through the implementation of stricter safety protocols and the development of more sustainable materials.

The integration of PAM with other technologies remains an area of great potential but also of considerable challenge. For instance, while slice-based photopolymerization techniques have improved the detail and continuity of printed structures, further advancements are required to expand the versatility of these methods (Wu & Dong, 2023). Additionally, material jetting technology has demonstrated potential in creating high-performance micromolds with conformal cooling channels, yet there remains a need for further research to fully understand its capabilities and limitations (Arrivabeni et al., 2023).

In conclusion, while PAM has substantially progressed the field of micromold fabrication, numerous challenges remain, particularly concerning material innovation, process optimization, scalability, and sustainability. Addressing these issues is crucial to realizing PAM's full potential and expanding its applicability across various high-precision industries. The ongoing developments in photopolymerization techniques, coupled with advancements in material science, offer promising avenues for overcoming current limitations and enhancing the capabilities of PAM.

Research Question

1. How do recent advancements in vat photopolymerization techniques and materials impact the effectiveness and precision of micromold applications in Additive Manufacturing (AM)?

2. What are the key materials science and engineering challenges faced in the development of new 3D printing technologies, and how are recent innovations addressing these challenges in various applications?

Material and Methods

A commonly accepted method for performing systematic literature reviews is the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, ensuring transparency, completeness, and consistency throughout. By adhering to PRISMA

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guidelines, researchers are guided to systematically identify, screen, and include studies in their review, thereby enhancing the accuracy and rigor of their analysis. The approach also underscores the significance of randomized studies for minimizing bias and providing robust evidence. In this analysis, two key databases, Scopus and Web of Science, were utilized for their comprehensive coverage and reliability. Scopus offers an extensive index of peer-reviewed literature across various disciplines. At the same time, the Web of Science (WoS) provides advantages such as a broad scope of coverage across multiple fields, rigorous indexing of high-impact journals, and tools for citation analysis. However, it is important to recognize that no database is without limitations; each has its coverage gaps and varying levels of detail that must be considered during the review process.

The four key sub-sections of the PRISMA technique are identification, screening, eligibility, and data abstraction. Finding all pertinent studies requires examining databases for identification. After that, studies are screened by evaluating them against predetermined standards to weed out irrelevant or subpar research. The remaining studies are further assessed during the eligibility phase to ensure they satisfy the inclusion requirements. Ultimately, data abstraction is the process of gathering and combining information from the included studies to create trustworthy and relevant findings. This methodical methodology guarantees a high degree of rigor in the systematic review, yielding dependable data that can guide future study and practice.

Identification

Crucial steps from the systematic review process were utilized in the present investigation to gather a substantial quantity of pertinent literature. Selecting keywords was the first step in the procedure. Next, similar terms were looked up using thesauri, dictionaries, encyclopedias, as well as previous research. Search strings for the Web of Science and Scopus databases were generated when pertinent phrases were found (refer to Table 1). Here, 196 papers pertaining to the study issue were determined in these two databases during the systematic review's first phase.

Table 1: The Search String.

Scopus	TITLE-ABS-KEY (photopolymerization AND ("additive manufacturing" OR "3D print*" OR "3-D print*") AND (micromold OR mold*)) AND PUBYEAR > 2021 AND PUBYEAR < 2025 AND (LIMIT-TO (SUBJAREA, "MATE") OR LIMIT-TO (SUBJAREA, "ENGI")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (PUBSTAGE, "final")) **Date of Access: Aug 2024**
Wos	TS=(photopolymerization AND ("additive manufacturing" OR "3D print*" OR "3-D print*") AND (micromold OR mold*)) and 2024 or 2023 or 2022 (Final Publication Year) and Article (Document Types) and Materials Science Multidisciplinary or Engineering Manufacturing or Nanoscience Nanotechnology (Web of Science Categories) **Date of Access: Aug 2024**

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Screening

Potentially pertinent research items are assessed in the screening process to ensure they support the predetermined research topic or questions. Choosing research items based on PAM for micromold application is common at this phase. At this point, duplicate documents are eliminated. Seventy-two papers were left for additional analysis based on particular inclusion and exclusion criteria after the first 196 publications were eliminated (refer to Table 2). As the main source of practical guidance, the literature was the first criterion to be considered. This covers book reviews, meta-analyses, conference proceedings, book series, meta-syntheses, as well as chapters that were left out of the most recent research. Only English-language publications from 2022 to 2024 were included in the review. Due to duplication, 21 publications were eliminated.

Table 2: The Selection Criterion Is Searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Timeline	2022 – 2024	< 2022
Literature type	Journal (Article)	Conference, Book, Review
Publication Stage	Final	In Press
Subject	Material Science and Engineering	Besides Material Science and Engineering

Data Abstraction and Analysis

An integrative analysis was one of the evaluation processes used in this investigation, which examined as well as synthesized a variety of research designs (quantitative methods). The competence study aimed to identify essential topics as well as their subtopics. The data collection phase was the first stage of the theme's development. Figure 2 illustrates the method by which the authors meticulously reviewed a collection of 28 articles to look for arguments or details relevant to the topics of the present research.

Consequently, the authors evaluated the significant recent research on PAM pertaining to micromolds. Assessments are being carried out on the research results and the methodologies used in each study. The author then worked together with the other co-authors to develop themes based on the study's background data. A log was kept during the data analysis process to document observations, thoughts, and riddles as well as other ideas relevant to the data interpretation. Ultimately, the authors compared the results to see if there was any inconsistency in the theme design process. It is significant to observe that the authors express any disagreements regarding their respective conceptions.

To address any disparities in the theme creation procedure, the authors additionally compared their findings. It should be noted that the writers discuss any discrepancies that may have arisen regarding the concepts. Ultimately, minor adjustments were made to the generated concepts to guarantee consistency. Two experts - one with a specialty in industrial product design and the other in additive manufacturing - performed the examinations to verify the validity of the issues. By demonstrating domain validity, the expert review stage contributed to ensuring the sufficiency, clarity, as well as importance of each sub-theme. The author has made changes at their discretion in response to expert opinions and input.

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Quality of Appraisal

As outlined by Kitchenham and Charters (Kitchenham, 2007), the Quality Assessment (QA) guidelines require evaluation and a quantitative comparison. This study applies the QA framework from (Abouzahra et al., 2020), which consists of six QAs (see Table 3), to conduct a systematic literature review The scoring procedure for evaluating each criterion involves three possible ratings: "Yes" (Y) with a score of 1 if the criterion is fully met, "Partly" (P) with a score of 0.5 if the criterion is somewhat met but contains some gaps or shortcomings, and "No" (N) with a score of 0 if the criterion is not met at all.

Table 3: The Quality Appraisal.

Quality Assessment	Expert 1	Expert 2	Expert 3	Total Mark
Is the purpose of the study clearly stated?	Y	Y	Y	3
Is the interest and the usefulness of the work clearly presented?	Y	Y	Y	3
Is the study methodology clearly established?	Y	Y	Y	3
Are the concepts of the approach clearly defined?	Y	Y	Y	3
Is the work compared and measured with other similar work?	Y	Y	Y	3

The table outlines a QA process used to evaluate a study based on specific criteria. Three experts assess the study using the criteria listed, and each criterion is scored as "Yes" (Y), "Partly" (P), or "No" (N). Here's a detailed explanation:

1. **Is the purpose of the study clearly stated?**
    - This criterion checks whether the study's objectives are clearly defined and articulated. A clear purpose helps set the direction and scope of the research.
2. **Is the interest and usefulness of the work clearly presented?**
    - This criterion evaluates whether the study's significance and potential contributions are well-explained. It measures the relevance and impact of the research.
3. **Is the study methodology clearly established?**
    - This assesses whether the research methodology is well-defined and appropriate for achieving the study's objectives. Clarity in methodology is crucial for the study's validity and reproducibility.
4. **Are the concepts of the approach clearly defined?**
    - This criterion looks at whether the theoretical framework and key concepts are clearly articulated. Clear definitions are essential for understanding the study's approach.
5. **Is the work compared and measured with other similar work?**
    - This evaluates whether the study has been benchmarked against existing research. Comparing with other studies helps position the work within the broader academic context and highlights its contributions.

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Each expert independently assesses the study according to these criteria, and the scores are then totaled across all experts to determine the overall mark. For a study to be accepted for the next process, the total mark, derived from summing the scores from all three experts, must exceed 3.0. This threshold ensures that only studies meeting a certain quality standard proceed further.

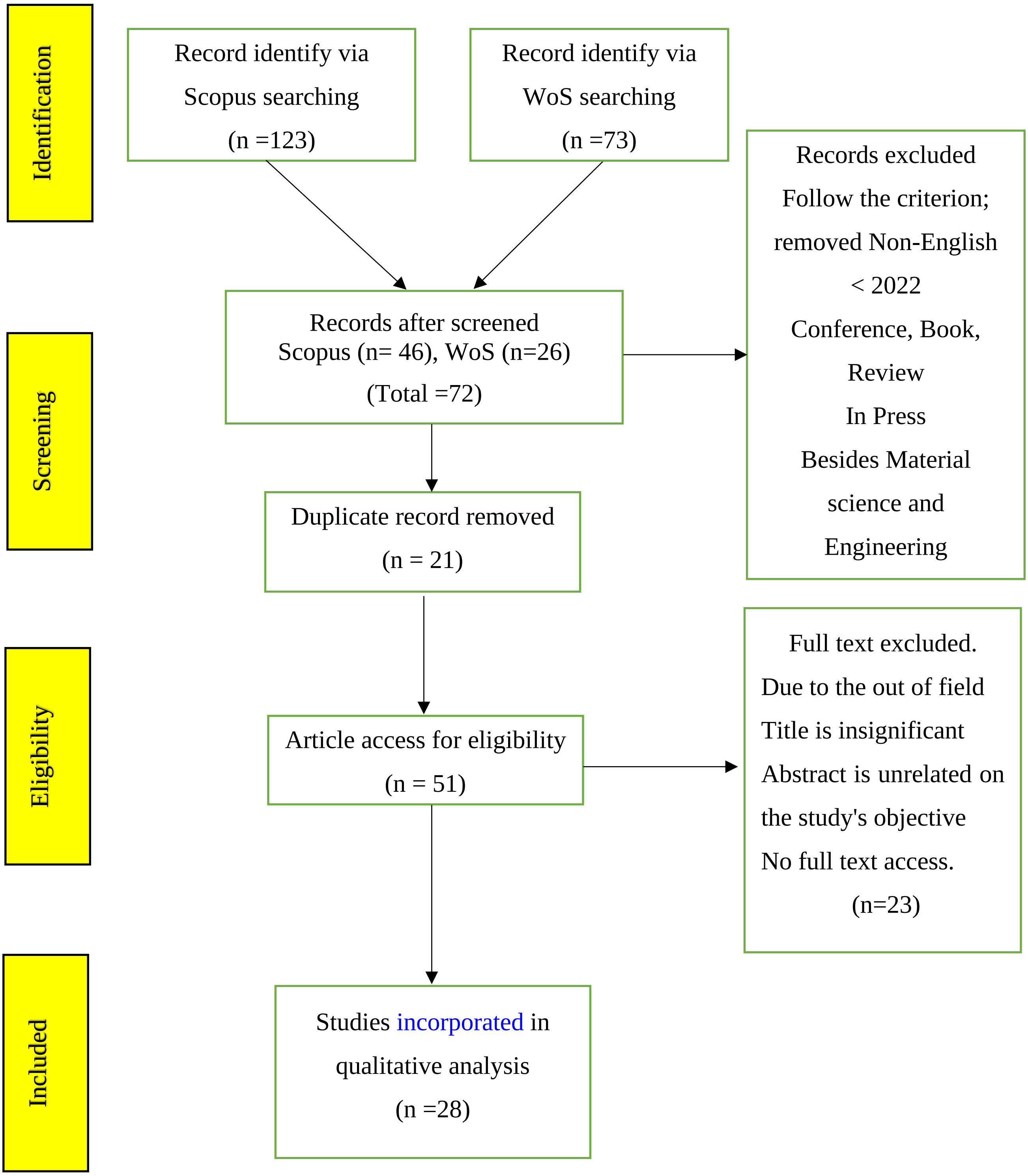

Figure 2. Flow Diagram Of The Proposed Searching Study

Result and Finding

Background of selected study:

No	Authors	Title	Year	Journal	Scopus	Web of Science
1	Li X.; Su H.; Dong D.; Jiang H.; Liu Y.; Shen Z.; Guo Y.; Hao S.; Zhang Z.; Guo M. (Li et al., 2024)	New approach to preparing near zero shrinkage alumina ceramic cores with excellent properties by vat photopolymerization	2024	Journal of Materials Science and Technology	/	/
2	Ritere A.; Jurinovs M.; Platnieks O.; Barkane A.; Gaidukovs S. (Ritere et al., 2024)	A super-tough plant oil based elastomer for UV-light assisted 3D printed soft robotics and shape-memory	2024	Journal of Materials Chemistry A	/	/
3	Yang Y.; Xu X.; Li Z.; Yao X.; Kang D.; Lu Y.; Wang Y.; Guo Y.; Wang X. (Yang et al., 2023)	Synthesis and properties of vat photopolymerization 3D-printing benzoxazine	2023	Materials Letters	/	/
4	Lee C.-U.; Chin K.C.H.; Boydston A.J. (C.-U. Lee et al., 2023)	Additive Manufacturing by Heating at a Patterned Photothermal Interface	2023	ACS Applied Materials and Interfaces	/	/
5	Schwarzer-Fischer E.; Zschippang E.; Kunz W.; Koplin C.; Löw Y.M.; Scheithauer U.; Michaelis A. (Schwarzer-Fischer et al., 2023)	CerAMfacturing of silicon nitride by using lithography-based ceramic vat photopolymerization (CerAM VPP)	2023	Journal of the European Ceramic Society	/	
6	Subirada F.; Paoli R.; Sierra-Agudelo J.; Lagunas A.; Rodriguez-Trujillo R.; Samitier J. (Subirada et al., 2022)	Development of a Custom-Made 3D Printing Protocol with Commercial Resins for Manufacturing Microfluidic Devices	2022	Polymers	/	
7	de Camargo I.L.; Lovo J.F.P.; Erbereli R.; Bock E.; Fortulan C.A. (de Camargo et al., 2022)	Fabrication of ceramics using photosensitive slurries: A comparison between UV-casting replication and vat photopolymerization 3D printing	2022	Processing and Application of Ceramics	/	
8	Zhang L.; Liu H.; Yao H.; Zeng Y.; Chen J. (L. Zhang et al., 2022)	3D printing of hollow lattice structures of ZrO2(3Y)/Al2O3 ceramics by vat	2022	Journal of Manufacturing Processes	/	/

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		photopolymerization: Process optimization, microstructure evolution and mechanical properties				
9	Tu R.; Kim H.C.; Sodano H.A. (Tu et al., 2023)	Additive Manufacturing of High-Temperature Thermoplastic Polysulfone with Tailored Microstructure via Precipitation Printing	2023	ACS Applied Materials and Interfaces	/	/
10	Rafalko C.; Stovall B.J.; Zimudzi T.; Hickner M.A. (Rafalko et al., 2023)	Tunable Stereolithography Photopolymerization Resin for Molding Water-Soluble Cavities	2023	ACS Applied Polymer Materials	/	/
11	Li X.; Su H.; Dong D.; Jiang H.; Liu Y.; Shen Z.; Guo Y.; Zhao D.; Zhang Z.; Guo M. (Li et al., 2023)	In-situ Y3Al5O12 enhances comprehensive properties of alumina-based ceramic cores by vat photopolymerization 3D printing	2023	Additive Manufacturing	/	/
12	Dinu E.; Spânu A.; Stănescu V.-A.; Moraru E.; Besnea D.; Constantin V.-F.; Rizescu C.; Panait I. (Dinu et al., 2023)	Considerations regarding the applications of additive manufacturing for the realization of sealing gaskets used in precision mechanics	2023	International Journal of Mechatronics and Applied Mechanics	/	
13	Poskus M.D.; Wang T.; Deng Y.; Borcherding S.; Atkinson J.; Zervantonakis I.K. (Poskus et al., 2023)	Fabrication of 3D-printed molds for polydimethylsiloxane-based microfluidic devices using a liquid crystal display-based vat photopolymerization process: printing quality, drug response and 3D invasion cell culture assays	2023	Microsystems and Nanoengineering	/	/
14	Cheng D.-Y.; Liao I.-H.; Yu J.; Liao Y.-C. (Cheng et al., 2022)	Highly compressible hydrogel reinforced with cellulose nanocrystals for ultrasound scanning via microwave-assisted synthesis	2022	Cellulose	/	
15	Zhang Y.; Gao Y.; Josien L.; Nouali H.; Vaulot C.; Simon-Masseron A.; Lalevée J. (Y. Zhang et al., 2022)	Photopolymerization of Zeolite Filler-Based Composites for Potential 3D Printing Application and Gas Adsorption Applications	2022	Advanced Materials Technologies		

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16	de Camargo I.L.; Fortulan C.A.; Colorado H.A.	A review on the ceramic additive manufacturing technologies and availability of equipment and materials	2022	Ceramica	/	
17	Liz-Basteiro P.; Sanz-Horta R.; Reviriego F.; Martínez-Campos E.; Reinecke H.; Elvira C.; Rodríguez-Hernández J.; Gallardo A.	High resolution molds, sacrificial in aqueous media, obtained by vat photopolymerization 3D printing	2023	Additive Manufacturing	/	/
18	Wu L.; Dong Z.	Interfacial Regulation for 3D Printing based on Slice-Based Photopolymerization	2023	Advanced Materials	/	/
19	She Y.; Chang H.; Tang J.; Guo X.; Zhu Y.; Liu G.; Yang X.; Hu X.; Huang Z.; Chen Z.; Yang Y.	Optimizing the properties of vat photopolymerization 3D-printed SiC ceramics by multi-infiltration	2024	Journal of Asian Ceramic Societies	/	
20	Lee D.; Kim D.H.; Kim H.; Seung H.M.; Song H.-C.; Kim M.	Engineering digital light processing ceramic composites for wide-range flexible sensing arrays	2024	Composites Part B: Engineering	/	
21	Shafique H.; Karamzadeh V.; Kim G.; Shen M.L.; Morocz Y.; Sohrabi-Kashani A.; Juncker D.	High-resolution low-cost LCD 3D printing for microfluidics and organ-on-a-chip devices	2024	Lab on a Chip	/	/
22	Ye Z.; Zhu L.; Zhou T.; Tong X.; Chen Z.; Zhou X.; Huang S.; Li Y.; Lin J.; Wen C.; Ma J.	Shear bond strength, finite element analysis, flexural strength and accuracy analysis of additively manufactured bio-inspired 3Y-TZP for dental applications	2024	Journal of Materials Research and Technology	/	/
23	Karam S.; Shirdade N.; Madden B.; Rheinstadter J.; Church E.W.; Brindise M.C.; Manogharan G.	Additive manufacturing of patient-specific high-fidelity and thickness-controlled cerebral aneurysm geometries	2023	Manufacturing Letters	/	/
24	Zhu G.; Zhang J.; Huang J.; Qiu Y.; Liu M.; Yu J.; Liu C.; Shang Q.; Hu Y.; Hu L.; Zhou Y.	Recyclable and reprintable biobased photopolymers for digital light processing 3D printing	2023	Chemical Engineering Journal	/	/
25	Yang X.; Wu T.; Liu D.; Wu J.; Wang Y.; Lu Y.; Ji Z.; Jia X.; Jiang P.; Wang X.	3D printing of release-agent retaining molds	2023	Additive Manufacturing	/	/

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26	Moharana A.P.; Raj R.; Dixit A.R.	Fabrication of continuous woven E-glass fiber composite using vat photopolymerization additive manufacturing process	2024	Rapid Prototyping Journal	/	/
27	Arrivabeni E.B.; Barbato M.C.; Giorleo L.	Thermo-fluid dynamics modelling of conformal cooling channels produced with material jetting technology	2023	International Journal of Mechatronics and Manufacturing Systems	/	
28	Becker R.; Kuenstler A.S.; Bowman C.N.	Photopolymerizable semi-crystalline polymers for thermally reversible, 3D printable cast molds	2024	Dental Materials	/	

The themes generated were refined to maintain consistency. Three experts conducted the analysis selection: Mohd Azmi Mazlan, who specializes in product design, and Mohd Raimi and Muhammad Shazwan, who are experts in the plastic injection manufacturing process. Their role was to assess and confirm the validity pertaining to the identified problems. By establishing domain validity, the expert review step made sure that each subtheme was understandable, pertinent, as well as appropriate.

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Vat Photopolymerization Techniques and Materials

Recent advances in VPP have enabled significant improvements when manufacturing ceramic components, especially when it comes to decreasing shrinkage and enhancing structural integrity. (Li et al., 2024) introduced an innovative atmosphere-controlled in-situ oxidation process for producing alumina ceramic cores with near-zero shrinkage. This method successfully achieved a remarkable reduction in linear shrinkage in the X direction to as low as 0.3%, together with high apparent porosity as well as flexural strength, demonstrating its potential for producing complex structures with superior properties. Similarly, (Yang et al., 2023) developed a novel benzoxazine monomer with low shrinkage and high printability, addressing the brittleness typically associated with benzoxazine, thus expanding its application potential in aerospace. Additionally, (She et al., 2024) proposed a multi-infiltration technique that significantly improved the mechanical properties of SiC ceramics, with elastic modulus increases of over 30%, showcasing the potential of VPP in producing high-performance ceramics.

The exploration of ceramic AM through VPP has also focused on optimizing microstructures and mechanical properties to meet the increasing demands for complex, high-precision components. (Schwarzer-Fischer et al., 2023) successfully applied VPP to produce silicon nitride components for biomedical applications, achieving complex geometries that enhance osseointegration. Their work highlighted the importance of formulation optimization to improve flow and curing behavior. Similarly, (L. Zhang et al., 2022) optimized the process parameters for producing ZrO_2(3Y)/Al_2O_3 hollow lattice structures, achieving a balance between high compressive strength and low porosity. The study demonstrated that careful control of slurry composition, degreasing, and sintering processes could prevent defects such as cracking and collapse, which are common challenges in ceramic AM. Correspondingly, these advancements indicate that VPP can effectively produce ceramic components with tailored properties for specialized applications.

Comparing various ceramic manufacturing techniques revealed the versatility as well as cost-effectiveness of VPP, particularly when using photosensitive slurries. (de Camargo et al., 2022) compared UV-casting replication and VPP, concluding that UV-casting is better suited for producing ceramic parts with larger cross-sections and higher flexural strength, even when using more viscous slurries. Additionally, (Li et al., 2023) explored the enhancement of alumina-based ceramic cores with in-situ $Y_3Al_5O_{12}$, achieving a significant reduction in high-temperature deflection while maintaining high porosity. This study, along with (Liz-Basteiro et al., 2023), who developed sacrificial molds using VPP for aqueous media applications, underscores the adaptability of VPP in producing complex ceramic structures with diverse functionalities. These findings highlight the ongoing evolution of VPP as a key technology in ceramic AM, offering innovative solutions to long-standing challenges in the industry.

Applications and Innovations in 3D Printing

Advancements in VPP technology have significantly enhanced the potential of AM, particularly in 3D printing for micro-molding and related applications. Recent research highlights the development of highly specialized materials that address the limitations of conventional manufacturing methods. For instance, (Ritere et al., 2024) demonstrated the creation of a 3D-printable plant oil-based elastomer with tunable mechanical properties, ranging from soft and stretchable to hard and shape-memory, specifically designed for soft robotics and other high-resolution applications. (C.-U. Lee et al., 2023) introduced a novel AM

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technique known as Heating at a Patterned Photothermal Interface (HAPPI), which enables the direct 3D printing of commercial silicone resins, a significant step forward in producing high-resolution, complex geometries with excellent material properties. Similarly, (Rafalko et al., 2023) developed a tunable SLA photopolymerization resin, enabling the creation of water-soluble cavities for molding applications, demonstrating the versatility and precision of VPP in producing intricate and complex parts.

Furthermore, integrating VPP with other technologies has opened new avenues for manufacturing microfluidic devices and high-temperature thermoplastics. (Subirada et al., 2022) explored the use of SLA in fabricating microfluidic devices, achieving successful pressure-driven fluid flow in 3D-printed channels, thereby paving the way for advancements in biological analysis and chemical detection. (Poskus et al., 2023) expanded on this by utilizing Liquid Crystal Display (LCD)-based VPP to fabricate molds for Polydimethylsiloxane (PDMS)-based microfluidic platforms, optimizing 3D printing parameters for enhanced cytocompatibility and resolution. Additionally, (Tu et al., 2023) applied precipitation printing to produce high-temperature thermoplastic Polysulfone (PSU) with tailored microstructures, offering scalability and the ability to manufacture high-performance components for demanding environments. These innovations collectively underscore the growing impact of VPP technology in advancing the precision, functionality, and application range of AM, particularly in fields requiring complex geometries and specialized material properties.

Materials Science and Engineering in 3D Printing

PAM has significantly improved the mechanical characteristics of various composites and materials used in 3D printing. (Cheng et al., 2022) demonstrated that incorporating Cellulose Nanocrystals (CNCs) into Polyacrylic Acid (PAA) hydrogels significantly improved compressive strength, elasticity, and strain recovery, making them suitable for ultrasound scanning applications. Similarly, (Y. Zhang et al., 2022) explored zeolite filler-based composites, finding that high filler content (80-95 wt%) under mild photopolymerization conditions greatly improved mechanical properties and maintained porosity, essential for gas adsorption applications. These studies underscore the versatility of PAM in producing composites with tailored properties, extending its use to fields requiring high-performance, lightweight materials with specific industrial applications.

In another significant development, (D. Lee et al., 2024) utilized DLP-based 3D printing to generate flexible ceramic composites with enhanced capacitive sensing capabilities by blending Barium Titanate ($BaTiO_3$) and Multi-Walled Carbon Nanotubes (MWCNT) fillers with a photocurable resin. This advancement in sensor technology illustrates the potential of PAM in developing highly sensitive and flexible sensors for various applications. Additionally, (Moharana et al., 2024) highlighted the use of VPP to fabricate continuous woven Glass Fiber-Reinforced Polymer Composites (GFRPCs), achieving enhanced tensile and flexural properties. Lastly, (Becker et al., 2024) introduced thermally reversible, 3D printable semi-crystalline polymers for dental cast molds, offering a novel approach to streamlining manufacturing processes. These innovations collectively emphasize PAM’s transformative potential in materials science and engineering, particularly in creating complex, high-performance components across various industrial and medical applications.

Discussion and Conclusion

Recent advancements in VPP have notably enhanced the production of ceramic components, particularly in minimizing shrinkage and improving structural integrity. Innovations such as atmosphere-controlled in-situ oxidation, novel benzoxazine monomers, and multi-infiltration techniques have broadened VPP's potential for fabricating high-performance ceramics with intricate structures. Other than that, research efforts have also optimized microstructures and mechanical properties for specialized applications, underscoring VPP's versatility and cost-effectiveness in comparison to other ceramic manufacturing techniques. These developments establish VPP as a pivotal technology for addressing challenges in ceramic AM.

Progress in VPP has substantially broadened the scope of AM, especially in 3D printing for micro-molding and related applications. Recent innovations have introduced specialized materials and techniques that overcome the limitations of traditional manufacturing methods. Key achievements include the development of a 3D-printable plant oil-based elastomer with adjustable mechanical properties, the HAPPI technique for printing complex silicone resin geometries, and tunable SLA resins for molding applications. Furthermore, integrating VPP with other technologies has advanced the production of microfluidic devices and high-temperature thermoplastics, highlighting VPP's increasing role in enhancing the precision, functionality, and application range of AM.

PAM has recently made significant strides in improving the mechanical properties of various composites used in 3D printing. Hence, incorporating CNCs into PAA hydrogels has substantially enhanced compressive strength, elasticity, and strain recovery, making them ideal for ultrasound applications. Additionally, integrating zeolite fillers into composites has improved mechanical properties while maintaining porosity, which is essential for gas adsorption. PAM has also facilitated the creation of flexible ceramic composites with advanced capacitive sensing capabilities and the fabrication of continuous woven GFRPCs with superior tensile and flexural properties. Moreover, developing thermally reversible, 3D printable semi-crystalline polymers for dental molds offers a more efficient manufacturing approach. These advancements underscore PAM's growing influence in materials science, particularly in producing high-performance components for industrial and medical applications.

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Conflicts of Interest

The research's authors claim that they have no conflicts of interest to disclose.

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References

Aabith, S., Caulfield, R., Akhlaghi, O., Papadopoulou, A., Homer-Vanniasinkam, S., & Tiwari, M. K. (2022). 3D direct-write printing of water soluble micromoulds for high-resolution rapid prototyping. *Additive Manufacturing*. https://doi.org/10.1016/j.addma.2022.103019

Abouzahra, A., Sabraoui, A., & Afdel, K. (2020). Model composition in Model Driven Engineering: A systematic literature review. *Information and Software Technology*, *125*(May), 106316. https://doi.org/10.1016/j.infsof.2020.106316

Arrivabeni, E. B., Barbato, M. C., & Giorleo, L. (2023). Thermo-fluid dynamics modelling of conformal cooling channels produced with material jetting technology. *International Journal of Mechatronics and Manufacturing Systems*, *16*(2–3), 225–242. https://doi.org/10.1504/IJMMS.2023.133399

Bean, R. H., & Long, T. E. (2024). Recent trends in the additive manufacturing of polyurethanes. In *Polymer International*. https://doi.org/10.1002/pi.6584

Becker, R., Kuenstler, A. S., & Bowman, C. N. (2024). Photopolymerizable semi-crystalline polymers for thermally reversible, 3D printable cast molds. *Dental Materials*, *40*(6), 976–983. https://doi.org/10.1016/j.dental.2024.05.009

Cao, L., Li, J., Hu, J., Liu, H., Wu, Y., & Zhou, Q. (2021). Optimization of surface roughness and dimensional accuracy in LPBF additive manufacturing. *Optics and Laser Technology*. https://doi.org/10.1016/j.optlastec.2021.107246

Cheng, D.-Y., Liao, I.-H., Yu, J., & Liao, Y.-C. (2022). Highly compressible hydrogel reinforced with cellulose nanocrystals for ultrasound scanning via microwave-assisted synthesis. *Cellulose*, *29*(18), 9791–9802. https://doi.org/10.1007/s10570-022-04854-6

Chuang, Y.-S., Berekute, A. K., Hsu, H.-Y., Wei, H.-S., Gong, W.-C., Hsu, Y.-Y., Tsai, C.-J., & Yu, K.-P. (2024). Assessment of emissions and exposure in 3D printing workplaces in Taiwan. *Journal of Occupational and Environmental Hygiene*, *21*(4), 270–286. https://doi.org/10.1080/15459624.2024.2313655

de Camargo, I. L., Lovo, J. F. P., Erbereli, R., Bock, E., & Fortulan, C. A. (2022). Fabrication of ceramics using photosensitive slurries: A comparison between UV-casting replication and vat photopolymerization 3D printing. *Processing and Application of Ceramics*, *16*(2), 153–159. https://doi.org/10.2298/PAC2202153C

Dinu, E., Spânu, A., Stănescu, V.-A., Moraru, E., Besnea, D., Constantin, V.-F., Rizescu, C., & Panait, I. (2023). CONSIDERATIONS REGARDING THE APPLICATIONS OF ADDITIVE MANUFACTURING FOR THE REALIZATION OF SEALING GASKETS USED IN PRECISION MECHANICS. *International Journal of Mechatronics and Applied Mechanics*, *2023*(14), 179–184. https://doi.org/10.17683/ijomam/issue14.21

Feng, Q., Hu, K., Wang, H., Qian, C., & Lu, Z. (2024). Forming deviation coupling model and control method in the photopolymerization process of ceramic slurry. *Ceramics International*, *50*(5), 8490–8499. https://doi.org/10.1016/j.ceramint.2023.12.184

Hegab, H., Khanna, N., Monib, N., & Salem, A. (2023). Design for sustainable additive manufacturing: A review. In *Sustainable Materials and Technologies*. https://doi.org/10.1016/j.susmat.2023.e00576

Jafari, D., Vaneker, T. H. J., & Gibson, I. (2021). Wire and arc additive manufacturing: Opportunities and challenges to control the quality and accuracy of manufactured parts. *Materials and Design*. https://doi.org/10.1016/j.matdes.2021.109471

Kitchenham, B. (2007). Guidelines for performing systematic literature reviews in software engineering. *Technical Report, Ver. 2.3 EBSE Technical Report. EBSE*.

Volume 6 Issue 19 (December 2024) PP. 21-39
DOI 10.35631/IJIREV.619002
Knowles, M. R. H. (2000). Micro-ablation with high power pulsed copper vapor lasers. *Optics Express*. https://doi.org/10.1364/oe.7.000050

Kuenstler, A. S., Hernandez, J. J., Trujillo-Lemon, M., Osterbaan, A., & Bowman, C. N. (2023). Vat Photopolymerization Additive Manufacturing of Tough, Fully Recyclable Thermosets. *ACS Applied Materials and Interfaces*. https://doi.org/10.1021/acsami.2c22081

Leary, E., Curran, S., Susienka, M., Manning, K. L., Blakely, A. M., & Morgan, J. R. (2017). Micro-moulded non-adhesive hydrogels to form multicellular microtissues – the 3D Petri Dish®. In *Technology Platforms for 3D Cell Culture*. https://doi.org/10.1002/9781118851647.ch5

Lee, C.-U., Chin, K. C. H., & Boydston, A. J. (2023). Additive Manufacturing by Heating at a Patterned Photothermal Interface. *ACS Applied Materials and Interfaces*, *15*(12), 16072–16078. https://doi.org/10.1021/acsami.3c00365

Lee, D., Kim, D. H., Kim, H., Seung, H. M., Song, H.-C., & Kim, M. (2024). Engineering digital light processing ceramic composites for wide-range flexible sensing arrays. *Composites Part B: Engineering*, *283*. https://doi.org/10.1016/j.compositesb.2024.111595

Li, X., Su, H., Dong, D., Jiang, H., Liu, Y., Shen, Z., Guo, Y., Hao, S., Zhang, Z., & Guo, M. (2024). New approach to preparing near zero shrinkage alumina ceramic cores with excellent properties by vat photopolymerization. *Journal of Materials Science and Technology*, *193*, 61–72. https://doi.org/10.1016/j.jmst.2023.12.063

Li, X., Su, H., Dong, D., Jiang, H., Liu, Y., Shen, Z., Guo, Y., Zhao, D., Zhang, Z., & Guo, M. (2023). In-situ Y3Al5O12 enhances comprehensive properties of alumina-based ceramic cores by vat photopolymerization 3D printing. *Additive Manufacturing*, *73*. https://doi.org/10.1016/j.addma.2023.103645

Liz-Basteiro, P., Sanz-Horta, R., Reviriego, F., Martínez-Campos, E., Reinecke, H., Elvira, C., Rodríguez-Hernández, J., & Gallardo, A. (2023). High resolution molds, sacrificial in aqueous media, obtained by vat photopolymerization 3D printing. *Additive Manufacturing*, *75*. https://doi.org/10.1016/j.addma.2023.103758

Mobarak, M. H., Islam, M. A., Hossain, N., Al Mahmud, M. Z., Rayhan, M. T., Nishi, N. J., & Chowdhury, M. A. (2023). Recent advances of additive manufacturing in implant fabrication – A review. In *Applied Surface Science Advances*. https://doi.org/10.1016/j.apsadv.2023.100462

Moharana, A. P., Raj, R., & Dixit, A. R. (2024). Fabrication of continuous woven E-glass fiber composite using vat photopolymerization additive manufacturing process. *Rapid Prototyping Journal*, *30*(2), 253–269. https://doi.org/10.1108/RPJ-02-2023-0062

Otero, N., Goh, G., Vidal, S. M., Sanmartin, D., Meggs, C., Button, T. W., & Romero, P. (2016). High precision direct fabrication by laser of micromoulds in PDMS for micro-replication. *Proceedings of the 16th International Conference of the European Society for Precision Engineering and Nanotechnology, EUSPEN 2016*.

Poskus, M. D., Wang, T., Deng, Y., Borcherding, S., Atkinson, J., & Zervantonakis, I. K. (2023). Fabrication of 3D-printed molds for polydimethylsiloxane-based microfluidic devices using a liquid crystal display-based vat photopolymerization process: printing quality, drug response and 3D invasion cell culture assays. *Microsystems and Nanoengineering*, *9*(1). https://doi.org/10.1038/s41378-023-00607-y

Rafalko, C., Stovall, B. J., Zimudzi, T., & Hickner, M. A. (2023). Tunable Stereolithography Photopolymerization Resin for Molding Water-Soluble Cavities. *ACS Applied Polymer Materials*, *5*(12), 10097–10104. https://doi.org/10.1021/acsapm.3c01965

Volume 6 Issue 19 (December 2024) PP. 21-39
DOI 10.35631/IJIREV.619002
Ritere, A., Jurinovs, M., Platnieks, O., Barkane, A., & Gaidukovs, S. (2024). A super-tough plant oil based elastomer for UV-light assisted 3D printed soft robotics and shape-memory. *Journal of Materials Chemistry A*, *12*(27), 16569–16582. https://doi.org/10.1039/d4ta02218a

Schwarzer-Fischer, E., Zschippang, E., Kunz, W., Koplin, C., Löw, Y. M., Scheithauer, U., & Michaelis, A. (2023). CerAMfacturing of silicon nitride by using lithography-based ceramic vat photopolymerization (CerAM VPP). *Journal of the European Ceramic Society*, *43*(2), 321–331. https://doi.org/10.1016/j.jeurceramsoc.2022.10.011

Shaukat, U., Rossegger, E., & Schlögl, S. (2022). A Review of Multi-Material 3D Printing of Functional Materials via Vat Photopolymerization. In *Polymers*. https://doi.org/10.3390/polym14122449

She, Y., Chang, H., Tang, J., Guo, X., Zhu, Y., Liu, G., Yang, X., Hu, X., Huang, Z., Chen, Z., & Yang, Y. (2024). Optimizing the properties of vat photopolymerization 3D-printed SiC ceramics by multi-infiltration. *Journal of Asian Ceramic Societies*, *12*(2), 164–171. https://doi.org/10.1080/21870764.2024.2330199

Subirada, F., Paoli, R., Sierra-Agudelo, J., Lagunas, A., Rodriguez-Trujillo, R., & Samitier, J. (2022). Development of a Custom-Made 3D Printing Protocol with Commercial Resins for Manufacturing Microfluidic Devices. *Polymers*, *14*(14). https://doi.org/10.3390/polym14142955

Tang, Y., Zhang, Y., Meng, Z., Sun, Q., Peng, L., Zhang, L., Lu, W., Liang, W., Chen, G., & Wei, Y. (2022). Accuracy of additive manufacturing in stomatology. In *Frontiers in Bioengineering and Biotechnology*. https://doi.org/10.3389/fbioe.2022.964651

Tu, R., Kim, H. C., & Sodano, H. A. (2023). Additive Manufacturing of High-Temperature Thermoplastic Polysulfone with Tailored Microstructure via Precipitation Printing. *ACS Applied Materials and Interfaces*, *15*(38), 45270–45280. https://doi.org/10.1021/acsami.3c09048

Wu, L., & Dong, Z. (2023). Interfacial Regulation for 3D Printing based on Slice-Based Photopolymerization. *Advanced Materials*, *35*(29). https://doi.org/10.1002/adma.202300903

Yang, Y., Xu, X., Li, Z., Yao, X., Kang, D., Lu, Y., Wang, Y., Guo, Y., & Wang, X. (2023). Synthesis and properties of vat photopolymerization 3D-printing benzoxazine. *Materials Letters*, *345*. https://doi.org/10.1016/j.matlet.2023.134448

Yue, L., Su, Y.-L., Li, M., Yu, L., Sun, X., Cho, J., Brettmann, B., Gutekunst, W. R., Ramprasad, R., & Qi, H. J. (2024). Chemical Circularity in 3D Printing with Biobased Δ-Valerolactone. *Advanced Materials*. https://doi.org/10.1002/adma.202310040

Zhang, F., Wei, M., Viswanathan, V. V., Swart, B., Shao, Y., Wu, G., & Zhou, C. (2017). 3D printing technologies for electrochemical energy storage. *Nano Energy*, *40*, 418–431. https://doi.org/10.1016/j.nanoen.2017.08.037

Zhang, K., Meng, Q., Qu, Z., & He, R. (2024). A review of defects in vat photopolymerization additive-manufactured ceramics: Characterization, control, and challenges. In *Journal of the European Ceramic Society*. https://doi.org/10.1016/j.jeurceramsoc.2023.10.067

Zhang, L., Liu, H., Yao, H., Zeng, Y., & Chen, J. (2022). 3D printing of hollow lattice structures of ZrO2(3Y)/Al2O3 ceramics by vat photopolymerization: Process optimization, microstructure evolution and mechanical properties. *Journal of Manufacturing Processes*, *83*, 756–767. https://doi.org/10.1016/j.jmapro.2022.09.047

Zhang, Y., Gao, Y., Josien, L., Nouali, H., Vaulot, C., Simon-Masseron, A., & Lalevée, J. (2022). Photopolymerization of Zeolite Filler-Based Composites for Potential 3D

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Volume 6 Issue 19 (December 2024) PP. 21-39
DOI 10.35631/IJIREV.619002

Printing Application and Gas Adsorption Applications. *Advanced Materials Technologies*, *7*(3). https://doi.org/10.1002/admt.202100869