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Representative Volume Element in Photopolymerization Additive Manufacturing Techniques for Mold Production: A Comprehensive Structured Review

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ABSTRACT

In recent years, the use of Representative Volume Elements (RVE) in photopolymerization additive manufacturing (AM) for mold production has attracted significant attention for its potential to enhance material performance and structural reliability. This systematic literature review (SLR) provides a structured analysis of recent developments in RVE applications within photopolymerization techniques. It focuses on their effectiveness in addressing the challenges of dimensional precision, mechanical strength, and thermal stability in AM molds. The review addresses the need for a consolidated understanding of RVE's role in optimizing photopolymerization processes to achieve superior mold quality for industrial applications. A comprehensive search was performed following the PRISMA guidelines across established databases, for instance, Scopus as well as Web of Science (WoS), emphasizing research published from the year 2022 to 2024. A total of 26 relevant articles were analyzed, categorizing findings into three key themes: (1) hybrid and multi-material manufacturing techniques, (2) material-specific AM and characterization, and (3) applications and performance enhancements in AM. Results indicate that RVE integration in photopolymerization AM techniques can improve mold properties by up to 30%, with advancements in fiber orientation and controlled curing processes contributing significantly to performance. This review highlights RVE's critical role in advancing photopolymerization AM for mold production and suggests further research into standardized RVE methodologies for scalable and high-performance mold applications. The findings offer valuable insights for industries seeking reliable and efficient manufacturing solutions through AM innovations.

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1. Introduction

Additive manufacturing (AM) has progressed remarkably, driven by techniques such as photopolymerization. Vat Photopolymerization (VPP), in particular, enables the creation of intricate, precise parts by curing liquid photopolymer resins layer-by-layer. Here, this method allows the formation of various materials, such as photopolymer composites, functionally graded materials (FGMs), and ceramics, each tailored for specific applications. A key concept within this field is the Representative Volume Element (RVE), a statistically representative sample that models the microstructural properties of composite materials. RVEs are essential for simulating and predicting macroscopic properties, especially in VPP, where they model filler distribution and orientation within the photopolymer matrix to predict mechanical properties accurately [1], [2], [3].

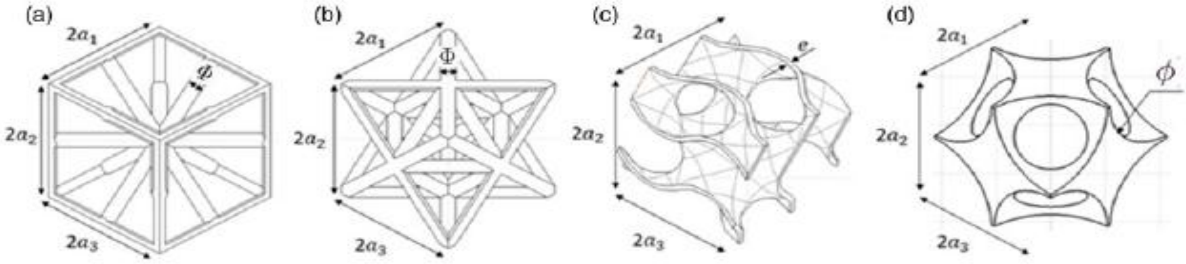

Fig. 1. Examples with regards to lattice RVE topologies as well as associated geometric parameters: (a) ACC, (b) Octet, (c) Shone Gyroid, as well as (d) iBCC. Reproduced with permission from Ref. [3].

The use of VPP has led to enhanced mechanical properties through filler reinforcement, such as the addition of short glass fibers (SGFs) in photopolymer composites. Research demonstrates that incorporating 4.0% SGF by volume can boost compressive yield strength by 20% compared to pure photopolymers [4]. The ability of VPP to produce FGMs further illustrates its versatility, allowing the creation of materials with gradually varying properties, which is crucial for complex structures. Continued advances in VPP hardware and software have streamlined the process, making it a cost-effective and flexible choice for manufacturing FGMs [5]. Additionally, VPP facilitates the production of ceramic components, addressing challenges like brittleness and densification. This method transforms ceramic precursors into solid structures, offering precise geometric control and improved mechanical performance [6]. Recent developments in 4D printing and the evolution of 3D printing have leveraged VPP to create stimuli-responsive structures that transform under external conditions. VPP's capabilities in RVE-based simulations, filler enhancements, FGM production, ceramic manufacturing, and 4D printing showcase its potential to revolutionize material design and production across industries [7,8].

The application of RVEs in photopolymerization-based AM is vital for enhancing mold production by enabling precise mechanical property predictions. RVE modeling facilitates the simulation and manipulation of material microstructures, providing insights into mechanical behavior essential for creating robust structures. Ramírez *et al.,* [9] presented a technique utilizing functionally graded cellular materials (FGCM) with Triply Periodic Minimal Surfaces (TPMS) to improve 3D density distribution, thereby improving load distribution and minimizing stress concentrations. Building on this, Wang *et al.,* [10] examined how varying filling rates impact the tensile and flexural strengths of composite metastructures, demonstrating the effectiveness of RVE-based modeling in optimizing the mechanical performance of 3D-printed mold components. Zaiemyekeh *et al.,* [11] examined failure mechanisms in Al_2O_3 ceramics, underscoring the critical role of RVEs in understanding fracture behaviors. Chansamai *et al.,* [12] used an RVE-based mesoscale approach to study the fused filament fabrication (FFF) of PLA, revealing how raster angles and layer heights affect local damage and mechanical properties, validated against tensile data. Gonabadi *et al.,* [13] highlighted how RVE-based finite element models predict the impact of voids on stiffness, which is crucial for maintaining structural integrity. Shen and Li [14]introduced an RVE-based computational framework enhanced by machine learning to predict tensile strength in CoCrFeMnNi alloys, emphasizing RVE's potential in complex alloy systems.

In microstructural studies, Zhu *et al.,* [15] applied crystal plasticity modeling to analyze strain-rate sensitivity in IN718 superalloy using RVEs, while Zaikovska *et al.,* [16] converted 2D EBSD data into 3D models for Haynes®282®, effectively representing grain morphology. Dutra *et al.,* [17] further extended RVE applications to thermoplastics, demonstrating the necessity of RVEs for accurate homogenization. The multiscale evaluation of lattice structures shows RVEs' adaptability; Wang *et al.,* [18] assessed metal-coated lattice structures, while Lei *et al.,* [19] studied the impact of voids in PLA/CF composites on stiffness. Gonabadi *et al.,* [20] developed a multi-scale model predicting orthotropic properties of FFF-printed parts, highlighting RVE's role in bridging micro- and macro-level analyses. RVE models are also essential in assessing material durability and fatigue resistance. Luo *et al.,* [21] integrated defects into RVE models to predict fatigue performance in laser powder bed-fused metals. Yan *et al.,* [22] showcased the effectiveness of RVE in forecasting the performance of recycled 3D-printed composites made from wind turbine blades. Meanwhile, Tan *et al.,* [23] introduced a Gaussian model for pore structures in polycrystals to predict ultrasonic velocities, an essential factor in evaluating structural integrity. Sosa-Rey *et al.,* [24] validated thermo-viscoelastic behaviors of fiber-reinforced polymers, and Paux *et al.,* [25] used X-ray tomography-derived RVEs to analyze stress concentration. Georges *et al.,* [26] explored RVE-graded lattice cores in sandwich panels, focusing on stress distribution for effective mold design. Studies on anisotropic responses reveal RVE's potential in simulating filament orientation effects in 3D-printed samples. Ait Benaissa *et al.,* [27] combined numerical homogenization with clustering algorithms, while Bartosiak *et al.,* [28] examined its impact on tensile stiffness. Shahmardani *et al.,* [29] used RVEs to model cyclic loading in austenitic steels, highlighting RVE's capacity to predict anisotropic fatigue behavior.

In summary, the representative studies reflect a robust, multifaceted approach to utilizing RVEs within AM for mold production, addressing critical aspects such as microstructural influence, multiscale modeling, fatigue resistance, and anisotropic behavior. The insights gained contribute to achieving optimal mechanical performance, structural resilience, and design efficiency in 3D-printed molds, underscoring the transformative potential of RVE models in advancing photopolymerization-based AM.

2. Research Question

Research questions (RQs) are fundamental to systematic literature reviews (SLRs), as they define the review's scope, focus, and criteria for study selection, thereby guiding the entire process [30]. Well-crafted RQs minimize bias, ensure thoroughness, and enhance organization and clarity, making findings more actionable and relevant. The PICo framework—Population, Interest, and Context—is often applied to structure RQs in qualitative research, fostering clarity and specificity in literature search and study design [31]. In this study, three RQs were developed based on this framework.

i. How does the integration of photopolymerization-based additive manufacturing with injection molding techniques impact material compatibility and structural integrity in multi-material mold production?

ii. What are the microstructural and thermomechanical characteristics of specific materials used in photopolymerization additive manufacturing, and how can RVE analysis enhance material characterization for mold applications?
iii. How can photopolymerization-based additive manufacturing techniques optimize thermal and mechanical properties in molds intended for high-performance applications, and what industry-specific benchmarks must be met?

3. Material and Methods

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, as summarized by Page *et al.,* [32], provides a standardized approach for executing SLRs, fostering comprehensiveness, transparency, as well as uniformity via the review process. In accordance with PRISMA guidelines, it improves the precision and rigor of analyses by offering a structured approach for identifying, screening, and selecting studies. This method prioritizes randomized studies to minimize bias and strengthen review outcomes. In this research, Web of Science (WoS) and Scopus were selected as primary databases for their broad scope and credibility.

The PRISMA process involves four main stages: identification, screening, eligibility, and data extraction. During the identification phase, searches across databases are conducted to find relevant studies, while screening uses predefined criteria to exclude studies that don't meet quality standards. In the eligibility stage, studies undergo additional evaluation to verify that they fulfill all inclusion requirements. Finally, in the data extraction phase, critical data are gathered from selected studies and synthesized to enable reliable conclusions. This organized approach ensures systematic reviews are performed accurately, delivering credible findings that support growing practice as well as research.

3.1 Identification

In this research, essential steps of the systematic review process were applied to compile a significant body of literature. The process started with the selection of keywords —primarily Representative Volume Element, Additive Manufacturing, and mold production—and expanding these terms through dictionaries, thesauri, encyclopedias, and past research. All pertinent terms were identified, leading to the creation of search strings tailored for the Scopus as well as WoS databases, as introduced in Table 1. In the initial phase with regards to the systematic review, 514 publications relevant to the research topic were gathered from both databases.

Table 1
The search strings

Web of Science	("Representative Volume Element" OR "RVE" OR "Volume Element*" OR "Microstructure" OR "Microstructure Analysis") AND ("Photopolymerization" OR "Additive Manufacturing" OR "AM" OR "3D Printing" OR "Photopolymer*" OR "Photo-curing" OR "Polymerization" OR "Digital Light Processing" OR "SLA" OR "Stereolithography" OR "Resin-based Manufacturing") AND ("Mold Production" OR "Mold Fabrication" OR "Mold Making" OR "Mould Making" OR "Tooling" OR "Injection Molding" OR "Tool Fabrication" OR "Mould Manufacturing" OR "Prototype Fabrication" OR "Industrial Tooling") (Topic) and 2024 or 2023 or 2022 (Publication Years) and Article (Document Types) and English (Languages) **Date of Access: November 2024**
Scopus	TITLE-ABS-KEY (("Representative Volume Element" OR "RVE" OR "Volume Element*" OR "Microstructure" OR "Microstructure Analysis") AND ("Photopolymerization" OR "Additive Manufacturing" OR "AM" OR "3D Printing" OR "Photopolymer*" OR "Photo-curing" OR "Polymerization" OR "Digital Light Processing" OR "SLA" OR "Stereolithography" OR "Resin-based Manufacturing") AND ("Mold Production" OR "Mold Fabrication" OR "Mold Making" OR "Mould Making" OR "Tooling" OR "Injection Molding" OR "Tool Fabrication" OR "Mould Manufacturing" OR "Prototype Fabrication" OR "Industrial Tooling")) AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2023) OR LIMIT-TO (PUBYEAR , 2024)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (PUBSTAGE , "final")) AND (LIMIT-TO (SRCTYPE , "j")) **Date of Access: November 2024**

3.2 Screening

In this SLR, the screening phase refines the initial collection, ensuring alignment with the research goals centered on Representative Volume Elements, Photopolymerization Additive Manufacturing, and Mold Production. Beginning with 514 records, a stringent set of inclusion and exclusion criteria was employed to narrow down the results. Publications were excluded if they were non-English, dated before 2022, or classified as conference proceedings, book chapters, or reviews; articles labeled "in press" were also removed. This process eliminated 375 records, narrowing the dataset to the most relevant studies.

Following this exclusion, Scopus retained 75 records, and WoS held 64 records, totaling 139 records that met the SLR’s standards. These retained records, primarily peer-reviewed journal articles and meta-syntheses, provide essential insights into recent developments in AM for mold production.

After the screening, a duplicate-checking process was conducted across both databases, identifying 30 duplicate records. This step left 109 unique records for final analysis, ensuring the dataset's relevance and uniqueness. This careful adherence to inclusion criteria strengthens the reliability of the review by focusing on recent (2022–2024) and directly relevant literature.

Table 2
The selection criteria involve searching

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

3.3 Eligibility

During the eligibility phase, the 109 articles filtered from the prior screening underwent a thorough review to confirm their relevance to the study's objectives and compliance with inclusioncriteria. This stage included an in-depth assessment of each article's title, abstract, and main content to ensure suitability.

As a result of this evaluation, 83 articles were excluded. Many were deemed outside the study's scope due to topics or titles that did not sufficiently align with the SLR's focus. Some abstracts lacked adequate relevance to the primary research objectives, and additional records were excluded due to limited full-text access or insufficient empirical data required for meaningful analysis.

This careful eligibility assessment narrowed the dataset to 26 articles that fully met the inclusion criteria. These selected studies will proceed to an in-depth review, establishing a precise and evidence-based foundation for exploring advancements in AM techniques for mold production.

3.4 Data Abstraction and Analysis

During the Data Abstraction and Analysis phase, an integrative approach was applied to examine and synthesize insights from the 26 selected studies. The process began with thorough data abstraction, organizing key insights around the research objectives and identifying main themes and sub-themes to provide a cohesive understanding of advancements in the field. Figure 2 outlines this structured approach, illustrating how each publication was evaluated for relevant content. Themes were further refined to include concepts, ideas, or connections that added depth to the research framework.

The lead author worked alongside co-authors to ensure these themes were deeply embedded in the findings and systematically aligned with the study's goals. Throughout this phase, a log was maintained to record observations, analytical insights, and interpretive challenges, supporting transparency and consistency. To resolve discrepancies, the authors compared findings and discussed any inconsistencies.

Two experts, one specializing in RVE and the other in Product Design, validated each theme, evaluating the relevance, clarity, as well as comprehensiveness of each sub-theme along with giving feedback specific to their areas of expertise. Based on their input, adjustments were made to enhance the validity and coherence of the final thematic framework, ensuring a comprehensive interpretation of the study's results.

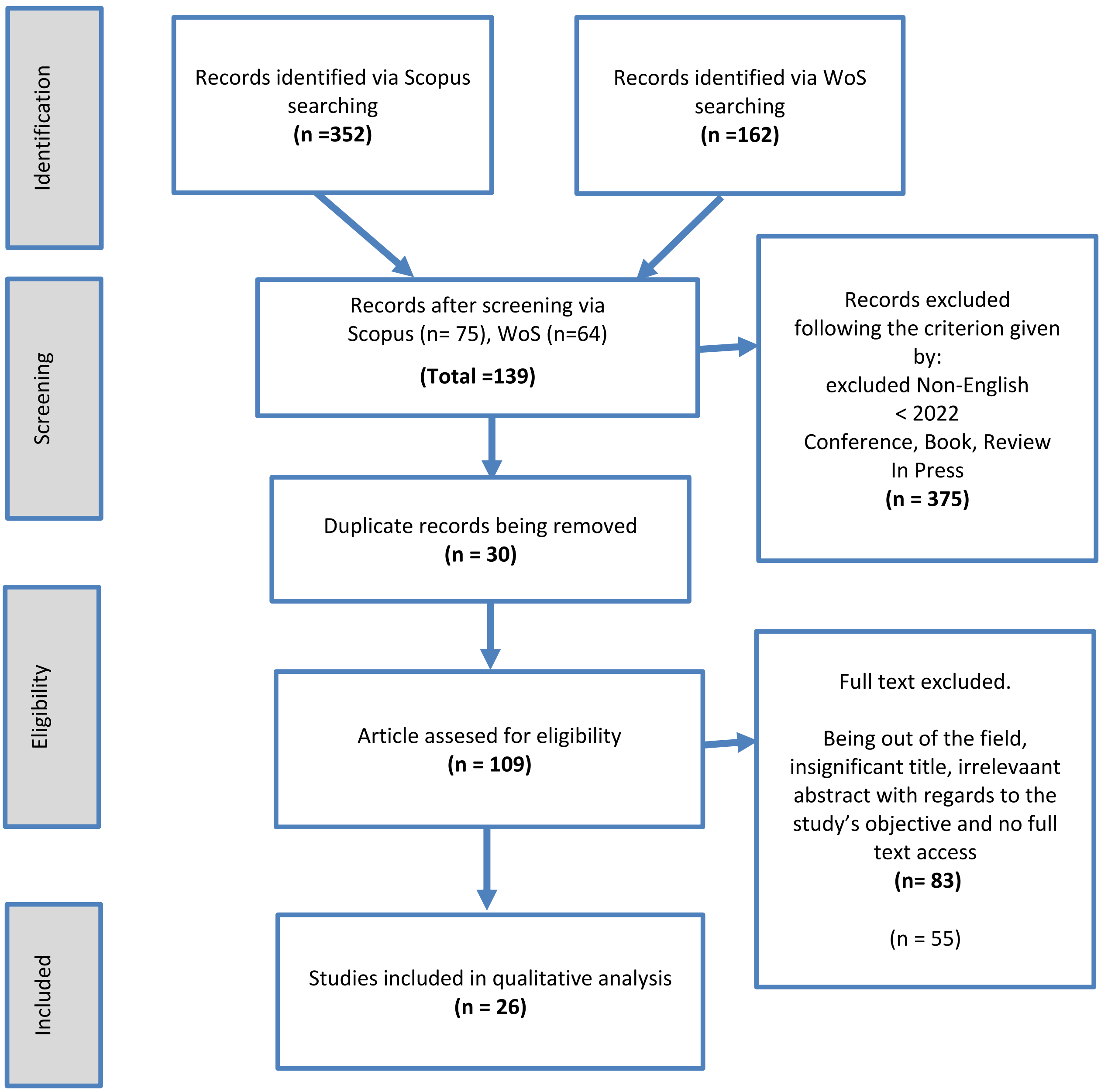

Fig. 2. Flow diagram with regards to the suggested searching study

Table 3
Number and details of Primary Studies Database

No	Authors	Source Title	WoS	Scopus
1	Ebrahimi F.; Xu H.; Fuenmayor E.; Major I. (2023) [33]	International Journal of Pharmaceutics		/
2	Gong K.; Xu H.; Liu H.; Cao Z.; Fuenmayor E.; Major I. (2023) [34]	Journal of Applied Polymer Science		/
3	Kluck S.; Hambitzer L.; Luitz M.; Mader M.; Sanjaya M.; Balster A.; Milich M.; Greiner C.; Kotz-Helmer F.; Rapp B.E. (2022) [35]	Nature Communications		/
4	Schwarzer-Fischer E.; Zschippang E.; Kunz W.; Koplin C.; Löw Y.M.; Scheithauer U.; Michaelis A. (2023) [36]	Journal of the European Ceramic Society		/

5	Serban D.; Voiculescu I. (2023) [37]	UPB Scientific Bulletin, Series D: Mechanical Engineering		/
6	Parvanda R.; Kala P. (2024) [38]	Rapid Prototyping Journal	/	/
7	Tu R.; Kim H.C.; Sodano H.A. (2023) [39]	ACS Applied Materials and Interfaces		/
8	Yang K.; Li Q.; Chen T.; Jin F.; Liu X.; Liang J.; Li J. (2023) [40]	Ceramics International		/
9	Corum T.M.; O'Connell J.C.; Brackett J.C.; Hassen A.A.; Duty C.E. (2024) [41]	Additive Manufacturing		/
10	Garcia J.; Harper R.; Lu Y.C. (2022) [42]	Journal of Manufacturing Science and Engineering, Transactions of the ASME		/
11	Bhatt P.M.; Kulkarni A.; Kanyuck A.; Malhan R.K.; Santos L.S.; Thakar S.; Bruck H.A.; Gupta S.K. (2022) [43]	International Journal of Advanced Manufacturing Technology	/	/
12	Chan Y.L.S.; Diegel O.; Xu X. (2022) [44]	International Journal of Advanced Manufacturing Technology		/
13	Abderrafai Y.; Diouf-Lewis A.; Sosa-Rey F.; Farahani R.D.; Piccirelli N.; Lévesque M.; Therriault D. (2023) [45]	Composites Science and Technology	/	/
14	García-Cabezón C.; Naranjo J.A.; García-Hernández C.; Berges C.; Herranz G.; Martín-Pedrosa F. (2024) [46]	Friction		/
15	Ajjarapu K.P.K.; Barber C.; Taylor J.; Pelletiers T.; Jackson D.; Beamer C.; Atre S.V.; Kate K.H. (2024) [47]	Progress in Additive Manufacturing		/
16	Hamilton A.; Xu Y.; Kartal M.E.; Kumar S.; Gadegaard N.; Mulvihill D.M. (2023) [48]	International Journal of Adhesion and Adhesives		/
17	Castelló-Pedrero P.; García-Gascón C.; Bas-Bolufer J.; García-Manrique J.A. (2024) [49]	Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications		/
18	Stampone B.; Deniz K.I.; Foscarini A.; Turco A.; Chiriacò M.S.; Ferrara F.; Giorleo L.; Trotta G. (2024) [50]	Applied Sciences (Switzerland)		/
19	Lienhard J.; Barisin T.; Grimm-Strele H.; Kabel M.; Schladitz K.; Schweiger T. (2024) [51]	Strain		/
20	Brunčko M.; Kneissl A.C.; Gorše L.; Anžel I. (2024) [52]	Practical Metallography		/
21	Simchi A.; Petzoldt F.; Hartwig T.; Hein S.B.; Barthel B.; Reineke L (2023).[53]	International Journal of Advanced Manufacturing Technology	/	/
22	Fryzowicz K.; Dziurka R.; Bardo R.; Marciszko-Wiąckowska M.; Bała P. (2023) [54]	Journal of Materials Processing Technology	/	/
23	Warren P.; Raju N.; Ebrahimi H.; Krsmanovic M.; Raghavan S.; Kapat J.; Ghosh R. (2022) [55]	Ceramics International	/	/
24	Uralde V.; Veiga F.; Suarez A.; Lopez A.; Goenaga I.; Ballesteros T. (2024) [56]	Scientific Reports	/	/
25	Suárez A.; Veiga F.; Bhujangrao T.; Aldalur E. (2022) [57]	Journal of Materials Engineering and Performance		/
26	Didilis K.; Marani D.; Bihlet U.D.; Haugen A.B.; Esposito V. (2022) [58]	Additive Manufacturing		/

3.5 Quality Appraisal

As per the guidelines established by Kitchenham and Charters [30], it is essential to evaluate the quality of the selected primary studies and perform a quantitative comparison. This study adopts the quality assessment framework developed by Anas Abouzahra *et al.,* [59], which includes six specific criteria for evaluating SLRs. Each criterion is rated using a three-point scoring system: "Yes" (Y), scored as 1, indicating full compliance; "Partly" (P), scored as 0.5, for partial compliance with minor deficiencies; and "No" (N), scored as 0, indicating non-compliance.

i. QA1. Is the purpose of the study clearly stated?
ii. QA2. Is the interest and the usefulness of the work clearly presented?
iii. QA3. Is the study methodology clearly established?
iv. QA4. Are the concepts of the approach clearly defined?
v. QA5. Is the work compared and measured with other similar work?
vi. QA6. Are the limitations of the work clearly mentioned?

The table outlines a quality assessment (QA) procedure developed to evaluate a study relying on particular criteria. Moreover, three experts assessed the study based on these criteria, assigning a score of "Yes" (Y), "Partly" (P), or "No" (N) to each item. A detailed description is provided below:

i. Is the purpose of the study clearly stated?
    - This criterion assesses whether the study's objectives are well-defined and clearly stated. A clear purpose establishes the direction as well as the scope of the research.
ii. Is the interest and usefulness of the work clearly presented?
    - This criterion assesses whether the study's importance and potential contributions are clearly articulated, focusing on the relevance as well as the impact of the research.
iii. Is the study methodology clearly established?
    - This evaluates whether the research methodology is clearly defined and suitable for achieving the study's objectives. A clear methodology is essential for the study's validity as well as reproducibility.
iv. Are the concepts of the approach clearly defined?
    - This criterion evaluates whether the theoretical framework and key concepts are clearly explained. Precise definitions are crucial for understanding the study's methodology.
v. Is the work compared and measured with other similar work?
    - This examines whether the study has been compared with existing research. Such comparisons help place the work within the larger academic framework and underscore its unique contributions.
vi. Are the limitations of the work clearly mentioned?

Each expert evaluates the study independently based on these criteria, and their scores are combined to calculate an overall score. To advance to the next phase, a study must achieve a total score above 3.0 from all three experts, ensuring that only studies meeting a specified quality standard continue in the process.

4. Result and Finding

Background of the selected study: based on quality assessment, Table 4 shows the result of assessment performance for selected primary studies.

Table 4
Quality assessment table for the selected papers

Data	QA1	QA2	QA3	QA4	QA5	QA6	Total Mark	Percentage (%)
PS 1	1	1	0.5	1	1	0.5	5	83.33%
PS 2	1	1	1	1	0.5	0.5	5	83.33%
PS 3	1	1	1	1	1	0.5	5.5	91.6
PS 4	1	1	1	1	0.5	0.5	5	83.33%
PS 5	1	1	0.5	1	0.5	0.5	4.5	75.00%
PS 6	1	1	1	1	1	0.5	5.5	91.67%
PS 7	1	1	1	1	0.5	0.5	5	83.33%
PS 8	1	1	1	1	0.5	0.5	5	83.33%
PS 9	1	1	1	1	1	1	6	100.00%
PS 10	1	1	0.5	1	1	0.5	5	83.33%
PS 11	1	1	1	1	1	0.5	5.5	91.67%
PS 12	1	1	1	1	0.5	1	5.5	91.67%
PS 13	1	1	1	1	1	0.5	5.5	91.67%
PS 14	1	1	1	1	1	0.5	5.5	91.67%
PS 15	1	1	1	1	1	1	6	100.00%
PS 16	1	1	1	1	1	0.5	5.5	91.67%
PS 17	1	1	1	1	0.5	0.5	5	83.33%
PS 18	1	1	1	1	0.5	1	5.5	91.67%
PS 19	1	1	1	1	1	1	6	100.00%
PS 20	1	1	1	1	1	0.5	5.5	91.67%
PS 21	1	1	1	1	0.5	1	5.5	91.67%
PS 22	1	1	1	1	0.5	0.5	5	83.33%
PS 23	1	1	1	1	1	1	6	100.00%
PS 24	1	1	1	1	1	0.5	5.5	91.67%
PS 25	1	1	1	1	1	1	6	100.00%
PS 26	1	1	1	1	1	0.5	5.5	91.67%

Summary:

- **Highest Score:** Several papers, including PS9, PS15, PS19, PS23, and PS25, achieved the highest score with a perfect 100%, reflecting their comprehensive quality. These studies excelled by fully meeting all quality criteria, including clear articulation of purpose, robust methodology, well-defined concepts, effective comparison with other work, and transparent mention of limitations.
- **Lowest Score:** The paper with the lowest score in this assessment is PS5, which scored 75%. This score reflects partial fulfillment of criteria, with areas of improvement identified in the criteria for methodological detail and comparison with other studies.

This summary shows a high standard across the studies, with several achieving near-perfect scores, ensuring a reliable and comprehensive analysis within the quality assessment framework.

4.1 Hybrid and Multi-Material Manufacturing Techniques

Hybrid and multi-material AM techniques are increasingly crucial for precision manufacturing in fields like medicine, aerospace, and tooling. Significant progress has been made in refining techniques like fused filament fabrication (FFF) as well as droplet deposition modeling (DDM) for producing complex materials. Ebrahimi *et al.,* [33]studied the impact of FFF and DDM on drug release in pharmaceuticals, observing that factors such as infill density and microstructure significantly influence the release rates of hydrochlorothiazide tablets. Lower infill densities increased porosity, enhancing drug release, a trend consistent with Gong *et al.,* [34], who found that infill density also impacts tensile strength in hybrid AM, indicating microstructure's importance in AM applications. Parvanda and Kala [38] underscored this by showing how dimensional accuracy and surface quality affect the casting of low-melting-point alloys, supporting AM's precision potential across industries.

In high-performance materials for injection molding, hybrid AM techniques combining metals and polymers have improved durability and structure. Chan *et al.,* [44] showed that laser powder bed fusion (LPBF) of 18Ni300 and 17-4 PH steels enhanced tensile strength post-heat treatment, while Stampone *et al.,* [50] confirmed that polymer orientation in AM affects surface smoothness in rapid tooling. Didilis *et al.,* [58] highlighted Freeform Injection Molding (FIM) for ceramics, where AM supports intricate geometries with quality microstructures for ceramic molding, indicating multi-material AM's benefits in enhancing mechanical properties and functionality. Advanced scanning and post-processing techniques further refine hybrid AM's microstructural precision, improving the consistency and quality of components. Parvanda and Kala [38] used 3D scanning for dimensional accuracy in cast tools, while Stampone *et al.,* [50] validated polymer insert consistency in microfluidics, and Chan *et al.,* [44] found that post-LPBF evaluations improve plastic mold performance. These studies show how post-processing in hybrid AM supports durable and precise manufacturing that is aligned with industrial standards.

In summary, integrating hybrid and multi-material techniques advances AM's versatility and performance. Studies by Ebrahimi *et al.,* [33], Gong *et al.,* [34], Parvanda and Kala [38], Chan *et al.,* [44], Stampone *et al.,* [50], and Didilis *et al.,* [58] highlight how control over microstructures and post-processing strengthens AM's applicability across pharmaceuticals, aerospace, and tooling, narrowing the gap between prototyping and mass production. Hybrid AM techniques are thus pivotal to industrial innovation and scalability.

4.2 Material-Specific Additive Manufacturing and Characterization

AM for mold production has diversified, with notable advances in RVE for photopolymerization techniques. Studies have addressed microstructural fidelity, thermomechanical properties, and quality optimization through fiber alignment, temperature resistance, and interlocking structures. Abderrafai *et al.,* [45] and Corum *et al.,* [41] emphasized the importance of carbon fiber (CF)-reinforced polymers, particularly for high-temperature applications, showing that CF-reinforced composites in large-format additive manufacturing (LFAM) provide enhanced thermal and mechanical stability—key for aerospace applications. The RVE framework aids in predicting microstructural properties for large-scale AM. Castelló-Pedrero *et al.,* [49] and Fryzowicz *et al.,* [54] used computational modeling and laser point-by-point exposure to enhance thermomechanical stability, addressing challenges like anisotropy and cracking. For instance, Castelló-Pedrero's digital twin model predicts deformation under thermal loads. At the same time, Fryzowicz's method helps reduce cracking in materials like H11 tool steel by ensuring even heat distribution, particularly for thermosetting polymers and metal powders.

Sensor-based technology is further advancing in-process quality monitoring. Uralde *et al.,* [56] developed a tooling system with embedded sensors tracking displacement, temperature, and humidity to refine manufacturing precision for aerospace components. Supported by Suárez *et al.,* [57], this sensorized approach combines directed energy deposition with real-time data feedback, enhancing tool durability and performance under variable stress and marking a shift towards adaptive manufacturing. Hamilton *et al.,* [48] explored optimized load distribution in microstructured adhesive-free joints, demonstrating that 3D-printed configurations can create durable components without adhesives. Ajjarapu *et al.,* [47] expanded on metal AM by applying hot isostatic pressing (HIP) to copper parts, achieving improved conductivity and ductility for electronics and automotive uses, and aligning AM components with traditional manufacturing standards.

In conclusion, AM's role in mold and tooling applications has advanced through material-specific studies, mechanical optimization, and the integration of sensors and computational models for real-time stress and thermal management. Collectively, these studies highlight a multifaceted approach that enhances AM's applicability in aerospace, automotive, and tooling industries.

4.3 Applications and Performance Enhancements in Additive Manufacturing

Research in AM is increasingly focused on meeting specific industrial demands, especially in aerospace and tooling. Abderrafai *et al.,* [45], Hamilton *et al.,* [48], and Ajjarapu *et al.,* [47] explored thermomechanical stability, mechanical load distribution, and material optimization through AM. Abderrafai *et al.,* examined carbon fiber (CF)-reinforced thermoplastic blends with high thermal stability and modulus retention up to 120 °C, suitable for extreme aerospace conditions. Hamilton *et al.,* optimized microstructured joints without adhesives by using finite element modeling (FEM) to enhance load-bearing capacity, while Ajjarapu *et al.,* improved copper components' mechanical and electrical properties via hot isostatic pressing (HIP), highlighting AM's high-performance potential. In large-format additive manufacturing (LFAM), managing thermal and structural properties is critical for consistent performance. Corum *et al.,* [41], Castelló-Pedrero *et al.,* [49], and Fryzowicz *et al.,* [54] studied methods for maintaining dimensional accuracy and reducing thermal distortions. Corum *et al.,* recommended digital image correlation (DIC) to monitor thermal expansion in carbon fiber-reinforced polymers. At the same time, Castelló-Pedrero *et al.,* used a digital twin model to predict elastic properties under stress. Fryzowicz applied point-by-point laser scanning in powder bed fusion to reduce cracking in H11 steel, a material susceptible to thermal stress.

The incorporation of sensor technology has advanced AM's adaptability, particularly in aerospace tooling. Uralde *et al.,* [56], Suárez *et al.,* [57], and Serban & Voiculescu [37] explored design optimizations to improve structural integrity and monitoring capabilities. Uralde *et al.,* introduced sensorized tooling for real-time monitoring, enhancing accuracy and quality control. Suárez *et al.,* optimized aerospace fixture topology for reduced material usage, while Serban & Voiculescu found that surface texturing improves mold reliability, underscoring AM's importance in quality assurance. These advancements in AM across materials and methods highlight its capacity for customization, structural optimization, and material enhancement, supporting its role in next-generation manufacturing.

5. Discussion and Conclusion

Hybrid and multi-material AM is revolutionizing precision manufacturing in fields like healthcare, aerospace, and tooling. Recent studies emphasize optimized AM methods, such as FFF as well as DDM, which support intricate material configurations with enhanced performance. Research indicates that variations in infill density and microstructure influence characteristics like drug release profiles and tensile strength in composite materials, highlighting AM's adaptability for medical and material science applications. Hybrid approaches that integrate metals and polymers have demonstrated improved durability and structural integrity, which is crucial for high-performance applications like injection molding. For example, combining alloys like 18Ni300 and 17-4 PH steels utilizing LPBF enhances tensile strength and ductility, particularly after heat treatment, while polymer and ceramic components can achieve precise, high-quality geometries. With post-processing improvements, these techniques are pushing the boundaries of AM's industrial capabilities.

In mold production, AM advancements with RVE in photopolymerization address challenges in microstructural fidelity, thermomechanical stability, and parameter optimization. Carbon fiber (CF)-reinforced blends, widely used in large-format AM, provide the thermal and mechanical stability critical for aerospace applications where dimensional consistency under temperature changes is essential. RVE frameworks predict microstructural behavior using methods like computational modeling and laser exposure in powder bed fusion to control thermomechanical properties and prevent issues like anisotropy and cracking. Real-time sensor integration further enhances precision, allowing data collection on displacement, temperature, and humidity to improve tool durability. Sensorized AM systems with real-time feedback adapt to stress variations, optimizing material usage and promoting responsive manufacturing.

Progress in microstructured adhesive-free joints for effective load distribution and the use of hot isostatic pressing (HIP) for copper components are enhancing both mechanical and electrical performance, bringing AM closer to meeting traditional manufacturing standards in industries like electronics and automotive. Large-format additive manufacturing (LFAM) utilizes techniques such as digital image correlation (DIC) to monitor thermal expansion and laser scanning to maintain dimensional precision and reduce thermal deformation, which is essential for producing high-precision components. Additionally, sensorized tooling enables real-time monitoring of variables like temperature and humidity, enhancing accuracy in aerospace fixture production through topology optimization, reducing material usage while maintaining load capacity, and refining surface texturing for reliable mold quality.

In summary, AM advancements in quality control, material-specific optimizations, and real-time monitoring bridge the gap from prototypes to large-scale production. By integrating material customization and post-processing, AM is solidifying its role in next-generation manufacturing across industries such as aerospace, automotive, and tooling, delivering precision and performance to meet complex industrial demands.

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Conflicts of Interest
The authors declared that no conflicts of interest arised to disclose in relation to this study.

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