Table 1.2 Brief chronicle of ceramic AM techniques and their pros/cons.

Category	Technique	Time first appeared	Applied to ceramics	Pros	Cons
Vat photopolymerization (VPP)	Stereolithography	1984 [63]	1993 [64]	Good resolution, large printing size	Scattering, large material volume is needed
	Digital light processing (for 3D printing)	1996~ [65]	2010~ [66]	Suitable speed	Medium size
	Two photopolymerization	1997~ [67]	2006 (for polymer-derived ceramics) [68]	High resolution	Very slow, small size
	Volumetric additive manufacturing	2017 [69]	2022 (for polymer-derived ceramics) [70]	No staircase effect	Small size
Material extrusion (MEX)	Direct ink writing	1998 [71]	2001~ [72]	Suitable for lattice structures	Low resolution, low surface quality, anisotropy
	Fused deposition modeling	1989 [73]	1995 [74]	High density	Low resolution
Material jetting (MJT)	Inkjet printing	1950~ [75]	1995~ [76]	Suitable for layered structures	Low solid content
Binder jetting (BJT)	Binder jetting	1989 [77]	1990 [78]	Versatility in material choices	Low resolution, low surface quality
Powder bed fusion (PBF)	Selective laser sintering	1986 [79]	1990 [80]	Versatility in material choices, large printing size	Low resolution, complicated post-treatments
	Selective laser melting (or direct laser sintering)	1996 [81]	1999~ [82, 83]	Versatility in material choices, large printing size	Low resolution, stress concentration
Sheet lamination (SHL)	Laminated object modeling	1984~ [84]	1994 [85]	High density	Layer bonding issues, anisotropy
Directed energy deposition (DED)	Laser-engineered net shaping	1996 [86]	2008 [87]	Large printing size	Low resolution, low surface quality

varying properties, as well as the combination of ceramics with other materials like metals or polymers, is also an area of expanding interest. This will enable the production of more complex and functional components for high-performance applications in aerospace, biomedical, and electronics industries.

Additionally, there is a growing focus on the development of equipment and processes that can handle multi-material ceramic AM. This includes improving feeding modes and coupling various process technologies (so-called hybridization) to create more advanced and versatile ceramic components. As the technology matures, we can expect to see more innovative applications of ceramic AM, pushing the boundaries of what is possible in terms of material properties, part complexity, and functionality.

In conclusion, AM of ceramics is a rapidly evolving field with significant potential for growth and innovation. As research and development continue to advance, we can anticipate a future where ceramic components are not only more precise and complex but also more functional and tailored to specific applications. Table 1.3 provides a detailed comparison between the features and characteristics of different types of ceramic AM techniques.

1.5 Summary of the Book

The continuous research and development in ceramics processing are driven by the need for materials and components with superior properties for increasingly demanding applications. As technology progresses, it is expected that new fabrication techniques will emerge, further enhancing the capabilities and performance of both traditional and advanced ceramics. The aim of this book is to comprehensively address the unique manufacturability challenges of ceramics through advanced AM technologies, bridging fundamental material science with process engineering. It provides an authoritative synthesis of AM principles and cutting-edge innovations to enable reliable fabrication of high-performance ceramic components across various applications and materials.

In this book, **Chapter 1** introduces the foundations of ceramic AM, which fostered ceramics' critical role across industries, highlighting their unique chemical stability, thermal resistance, and biocompatibility. It contrasts traditional manufacturing limitations with AM's capacity for geometric freedom, setting the stage for ISO/ASTM 52900 classification of AM processes. **Chapter 2** covers stereolithography (SLA) and DLP for ceramics using UV-cured ceramic suspensions. It compares top-down and bottom-up configurations, emphasizing high resolution and surface quality. Challenges include resin formulation, shrinkage during sintering, and support structures, while VAM revolutionizes production by curing entire 3D volumes in seconds, eliminating layer interfaces and surface features. **Chapter 3** discusses BJT and MJT technologies. BJT uses powder beds selectively bound by liquid agents, while MJT deposits ceramic suspensions droplet-by-droplet (e.g. via piezoelectric or thermal printheads). Applications include gypsum models, sand molds, and technical ceramics, with challenges in nozzle clogging, droplet fusion,

Table 1.3 Detailed features and characteristics of different types of ceramic AM techniques.

Category	Technique	Forming principle	Energy source	Feedstock form	Feedstock require-ments	Printing envelope	Resolution	Support needed	Speed	Surface quality	Overall cost
Vat photo-polymer-ization (VPP)	Stereolitho-graphy	Photopoly-merization	Light	Slurry	• Low viscosity	50 μm–100 cm	μm	Yes	★★★	★★★	★★
	Digital light processing	Photopoly-merization	Light	Slurry	• Low viscosity	100 μm–50 cm	μm	Yes	★★★	★★★	★★
	Two photo-polymer-ization	Photopoly-merization	Light	Slurry	• Low viscosity • Trans-parency	1 μm–1 mm	nm–μm	Yes	★	★★★	★★★
	Volumetric additive manu-facturing	Photopoly-merization	Light	Slurry	• Low viscosity • Trans-parency	100 μm–10 mm	μm–mm	No	★★★	★★★	★★★
Material extrusion (MEX)	Direct ink writing	Extrusion	Force	Slurry	• High solid content	100 μm–100 cm	μm–mm	Yes	★★★	★	★
	Fused deposition modeling	Extrusion	Heat/force	Filament	• Filament	100 mm–10 cm	mm	No	★★	★	★★
Material jetting (MJT)	Inkjet printing	Binding	Force	Slurry	• Low viscosity	100 μm–10 mm	mm	No	★★	★★★	★

(Continued)

Table 1.3 (Continued)

Category	Technique	Forming principle	Energy source	Feedstock form	Feedstock requirements	Printing envelope	Resolution	Support needed	Speed	Surface quality	Overall cost
Binder jetting (BJT)	Binder jetting	Binding	Force	Slurry/powder	• Binder required	10 mm–100 cm	μm–mm	No	★★★	★★	★★
Powder bed fusion (PBF)	Selective laser sintering	Fusion	Laser	Powder	• Binder required	10 mm–100 cm	μm–mm	No	★★★	★	★★★
	Selective laser melting	Fusion	Laser	Powder	• Good powder flowability	10 mm–100 cm	μm–mm	No	★★★	★	★★★
Sheet lamination (SHL)	Laminated object modeling	Binding	Laser	Sheet	• Sheet form	100 mm–100 cm	μm–mm	No	★★	★★	★
Directed energy deposition (DED)	Directed energy deposition	Fusion	Laser	Powder	• Good powder sphericity	10 mm–1000 cm	mm	Yes	★★★	★	★★★

Note: The number of ★ denotes the significance level.

and sintering shrinkage. **Chapter 4** details DIW and Fused Filament Fabrication (FFF) for ceramics. DIW relies on yield-stress ceramic inks for automated deposition, while FFF uses thermoplastic-ceramic filaments. Both methods enable complex geometries and multi-material structures but face challenges in shape fidelity, thermal gradients, and post-processing (debinding/sintering). Rheology and printability criteria are critically discussed. **Chapter 5** examines Selective Laser Sintering/Melting (SLS/SLM) and Electron Beam Melting (EBM) for ceramics. It distinguishes direct (full melting) and indirect (binder-assisted) approaches, addressing material constraints like electrical conductivity for EBM. Key challenges include dusting (powder bed instability), residual stresses, and achieving full density. Process optimization via parameter mapping is emphasized. **Chapter 6** explores laser-based DED for fabricating ceramic structures and composites. It highlights DED's ability to create monolithic ceramics (e.g. alumina and zirconia) and metal-ceramic functionally graded materials, enabling site-specific properties. Key challenges include thermal stress-induced cracking, limited material selection (excluding ultra-high-temperature melting ceramics), and scalability constraints due to inert atmosphere requirements. **Chapter 7** demonstrates hybrid AM (concurrent/sequential processes) and multi-material fabrication for ceramics, enabling freeform geometries, embedded features, and functional integration. It highlights strategies for co-sintering compatibility and stress management, with applications in heating elements, electronics, and SOFCs for next-generation multifunctional devices. **Chapter 8** comprehensively addresses computational design strategies, feedstock characterization protocols, and post-processing evaluation methods essential for ceramic AM. It details topology optimization for complex geometries, classifies feedstocks into powder-, liquid-, and bulk-solid-based systems with corresponding analytical techniques, and examines critical post-consolidation assessments, including anisotropic shrinkage control, thermomechanical stability, and defect minimization, to ensure structural integrity, especially in aerospace and biomedical applications. **Chapter 9** details industrial and consumer ceramic VPP differences, emphasizing industrial systems' material control, calibrated optics, and quality management for reproducibility. It explores multi-material LCM printing for enhanced mechanical properties and damage tolerance in complex ceramic components. **Chapter 10** explores diverse applications of ceramic AM, emphasizing its transformative impact across aerospace (lightweight satellite mirrors with integrated cooling channels), semiconductors (complex wafer-handling components), defense (high-performance radomes), energy (corrugated solid oxide cells for efficient hydrogen production), biomedical (customized implants and surgical tools), and environmental sectors (3D-printed coral substrates for reef restoration), leveraging technologies like stereolithography (SLA) to achieve unprecedented geometric complexity and functional integration. **Chapter 11** explores emerging frontiers in ceramic AM, focusing on green/smart design (recycled feedstocks, AI-driven process optimization), 4D printing (shape-morphing ceramics via differential sintering or hydrogel-ceramic bilayers), and 5D printing (multi-axis deposition for curved geometries), addressing sustainability challenges while enabling adaptive structures for advanced applications.

1.6 Conclusions

AM has fundamentally transformed ceramic fabrication, shattering geometric constraints and enabling unprecedented functional integration. From VPP's submicron precision to MJT's material gradients, each technology unlocks new possibilities in aerospace, biomedicine, energy, and other strategic sectors. While challenges like thermal cracking in PBF and debinding complexities in FFF persist, innovations in hybrid manufacturing and AI-driven process control demonstrate the field's adaptive resilience. The future lies in the convergence of sustainable material cycles, smart monitoring systems, and multifunctional designs – where ceramics evolve from passive components to active, adaptive elements, for instance, in quantum devices and personalized implants. As these technologies mature, they will not merely enable smart manufacturing of ceramics but will redefine their key role in an increasingly technologically sophisticated world.

AM has irrevocably transformed the fabrication landscape for advanced ceramics, overcoming intrinsic limitations of conventional methods such as geometric constraints, tooling costs, and machining brittleness. This book systematically discusses the major AM technologies: VPP, BJT, MJT, MEX, and PBF, demonstrating their unique capabilities in producing complex, high-performance ceramic components with tailored properties.

The future of ceramic AM research and development is likely to focus on improving the precision, strength, and functionality of ceramic parts, as well as expanding the range of materials that can be used in AM processes. The integration of different ceramic materials with varying properties, as well as the combination of ceramics with other materials like metals or polymers, is a growing area of interest, promising to open up extensive research opportunities in the realm of structural/functional ceramics.

- Key advancements highlighted include:
  - **High-resolution fabrication:** VPP techniques (TPP, VAM) achieve submicron features for micro-optics and biomedical devices, while MJT enables multi-material integration with droplet-level precision.
  - **Scalability:** BJT excels in large-format applications (e.g. architectural ceramics), and PBF supports high-temperature materials like ultra-high-temperature ceramics (UHTCs) for extreme environments.
  - **Material innovation:** Novel suspensions (DIW) and filaments (FFF) enhance sinterability, and hybrid processes (e.g. UV-assisted extrusion) combine speed with resolution and geometrical complexity.
- **Persistent challenges remain**
  - **Process-induced defects:** Thermal gradients in PBF cause cracking, requiring preheating or adaptive scanning strategies. Debinding/sintering complexities in BJT and FFF necessitate precise thermal profiles to avoid delamination. Furthermore, timely detection of these defects is of great importance to promote the upscaling of AM technologies into the industrial sector.
  - **Material limitations:** Non-oxide ceramics (SiC, Si_3N_4) demand inert atmospheres, while low-thermal-conductivity oxides (ZrO_2) struggle with thermal shock.

– **Standardization gaps:** Qualification protocols for critical applications (e.g. aerospace and implants) require further development.
- **Future directions emphasize**
  – **Smart manufacturing:** AI-driven real-time monitoring and closed-loop control to enhance reproducibility.
  – **Multifunctional systems:** Co-printing ceramics with metals or polymers for integrated sensors, energy harvesters, and bio-implants.
  – **Sustainability:** Recycling ceramic powders and bio-derived binders to reduce environmental impact.

In summary, ceramic AM bridges material science, process engineering, and digital design. It unlocks unprecedented opportunities for customized, high-value components across several key sectors, including aerospace, energy, and healthcare. As technology matures, interdisciplinary collaboration will be pivotal to harnessing its full potential, ultimately reshaping the future of advanced ceramics manufacturing.

References

1 Barsoum, M. (2019). *Fundamentals of Ceramics*. CRC Press.
2 Singh, S., Das, P.K., and Mondal, D. (2022). *Advanced Ceramics for Versatile Interdisciplinary Applications*. Elsevier.
3 Otitoju, T.A., Okoye, P.U., Chen, G. et al. (2020). Advanced ceramic components: materials, fabrication, and applications. *J. Ind. Eng. Chem.* 85: 34–65.
4 Dorey, R., Rocks, S., Dauchy, F. et al. (2008). Integrating functional ceramics into microsystems. *J. Eur. Ceram. Soc.* 28 (7): 1397–1403.
5 Drukteinis, S. and Camilleri, J. (2021). *Bioceramic Materials in Clinical Endodontics*. Springer.
6 Song, C., Ye, F., Cheng, L. et al. (2022). Long-term ceramic matrix composite for aeroengine. *J. Adv. Ceram.* 11 (9): 1343–1374.
7 Shim, J.H. (2018). Ceramics breakthrough. *Nat. Energy* 3 (3): 168–169.
8 Sengupta, P. (2020). *Refractories for the Chemical Industries*. Springer.
9 Justin, J. and Jankowiak, A. (2011). Ultra high temperature ceramics: densification, properties and thermal stability. *Aerosp. Lab* 3: 1–11.
10 Pastore, R., Delfini, A., Santoni, F. et al. (2021). Space environment exposure effects on ceramic coating for thermal protection systems. *J. Spacecr. Rocket.* 58 (5): 1387–1393.
11 Zhao, J., Pan, Z., Tang, L. et al. (2022). Greatly enhanced discharged energy density and efficiency of $BiFeO_3$-based ceramics by regulating insulation performance. *Mater. Today Phys.* 27: 100821.
12 Zhang, B., Ghassemi, M., and Zhang, Y. (2021). Insulation materials and systems for power electronics modules: a review identifying challenges and future research needs. *IEEE Trans. Dielectr. Electr. Insulat.* 28 (1): 290–302.
13 Wachtman, J.B., Cannon, W.R., and Matthewson, M.J. (2009). *Mechanical Properties of Ceramics*. Wiley.

14 Yu, Y., Wu, Y., Wang, B. et al. (2024). Review of the penetration resistance performance of lightweight ceramic composite armor under high-speed impact. *Mech. Adv. Mater. Struct.* 32: 1–23.

15 Shabani, M. and Gjoni, A. (2025). *Advancements in Hard Turning: Leveraging Ceramic Cutting Tools for Sustainable and High-Quality Metalworking, Advanced Ceramic Materials-Emerging Technologies*. IntechOpen.

16 McColm, I.J. (2013). *Ceramic Hardness*. Springer Science & Business Media.

17 Ikesue, A. and Aung, Y.L. (2008). Ceramic laser materials. *Nat. Photonics* 2 (12): 721–727.

18 Akinribide, O.J., Mekgwe, G.N., Akinwamide, S.O. et al. (2022). A review on optical properties and application of transparent ceramics. *J. Mater. Res. Technol.* 21: 712–738.

19 Hernandez, J.L. and Woodrow, K.A. (2022). Medical applications of porous biomaterials: features of porosity and tissue-specific implications for biocompatibility. *Adv. Healthcare Mater.* 11 (9): 2102087.

20 Kulkarni, S.V., Nemade, A.C., and Sonawwanay, P.D. (2022). An overview on metallic and ceramic biomaterials. *Recent Adv. Manuf. Process. Syst. Sel. Proc. RAM* 149–165.

21 Upadhyay, A., Pradhan, L., Yenurkar, D. et al. (2024). Advancement in ceramic biomaterials for dental implants. *Int. J. Appl. Ceram. Technol.* 21 (4): 2796–2817.

22 Evans, A.G. and Langdon, T.G. (1976). Structural ceramics. *Prog. Mater. Sci.* 21 (1–2): 171–425.

23 Padture, N.P. (2016). Advanced structural ceramics in aerospace propulsion. *Nat. Mater.* 15 (8): 804–809.

24 Noor, A.M., Abbas, M.R., Rajoo, S. et al. (2014). Review on ceramic application in automotive turbocharged engines. *Appl. Mech. Mater.* 660: 219–228.

25 Ikesue, A., Aung, Y.L., Taira, T. et al. (2006). Progress in ceramic lasers. *Annu. Rev. Mater. Res.* 36 (1): 397–429.

26 Khaliq, J. (2021). Ceramic matrix composites (CMCs). In Jibran Khaliq (Ed) *Advances in Machining of Composite Materials: Conventional and Non-conventional Processes*, 285–309. Springer.

27 Bansal, N.P. and Lamon, J. (2014). *Ceramic Matrix Composites: Materials, Modeling and Technology*. Wiley.

28 Kanyo, J.E., Schafföner, S., Uwanyuze, R.S., and Leary, K.S. (2020). An overview of ceramic molds for investment casting of nickel superalloys. *J. Eur. Ceram. Soc.* 40 (15): 4955–4973.

29 Bar-Cohen, Y. (2014). *High Temperature Materials and Mechanisms*. Boca Raton, FL: CRC Press.

30 Haubner, R., Herrmann, M., Lux, B. et al. (2003). *High Performance Non-Oxide Ceramics II*. Springer.

31 Katoh, Y. and Snead, L.L. (2019). Silicon carbide and its composites for nuclear applications–Historical overview. *J. Nucl. Mater.* 526: 151849.

32 Pushpakaran, B.N., Subburaj, A.S., Bayne, S.B., and Mookken, J. (2016). Impact of silicon carbide semiconductor technology in Photovoltaic Energy System. *Renew. Sust. Energ. Rev.* 55: 971–989.

33 Eray, E., Candelario, V.M., Boffa, V. et al. (2021). A roadmap for the development and applications of silicon carbide membranes for liquid filtration: recent advancements, challenges, and perspectives. *Chem. Eng. J.* 414: 128826.

34 Singh, S., Rathi, K., and Pal, K. (2018). Synthesis, characterization of graphene oxide wrapped silicon carbide for excellent mechanical and damping performance for aerospace application. *J. Alloys Compd.* 740: 436–445.

35 Behar-Lafenêtre, S., Louh, N., Grasset, P. et al. Silicon nitride for structural parts of space applications. *SPIE* 11101: 8–21.

36 Klemm, H. (2002). Corrosion of silicon nitride materials in gas turbine environment. *J. Eur. Ceram. Soc.* 22 (14–15): 2735–2740.

37 Blumenthal, D.J., Heideman, R., Geuzebroek, D. et al. (2018). Silicon nitride in silicon photonics. *Proc. IEEE* 106 (12): 2209–2231.

38 Ramachandran, K., Bear, J.C., and Jayaseelan, D.D. (2025). Oxide-based ceramic matrix composites for high-temperature environments: a review. *Adv. Eng. Mater.* 27: 2402000.

39 Lin, L., Liu, B., Zhang, T. et al. (2024). Analysis on carbonization evolution behavior of tungsten carbide powders and its application in cutting tools. *Int. J. Refract. Met. Hard Mater.* 118: 106447.

40 Sharath, B.N., Jeevan, T.P., Baig, M.A.A. et al. (2021). Machinability studies on boron carbide and graphite reinforced aluminium hybrid composites. *Mater. Today Proc.* 46: 8734–8741.

41 Wuchina, E., Opila, E., Opeka, M. et al. (2007). UHTCs: ultra-high temperature ceramic materials for extreme environment applications. *Electrochem. Soc. Interf.* 16 (4): 30.

42 Marques, A., Miranda, G., Silva, F. et al. (2021). Review on current limits and potentialities of technologies for biomedical ceramic scaffolds production. *J. Biomed. Mater. Res. B Appl. Biomater.* 109 (3): 377–393.

43 Chen, S., Ding, Y., Mu, H. et al. (2025). Research progress on multilayer ceramic capacitors for energy storage. *J. Mater. Sci. Mater. Electron.* 36 (1): 77.

44 Testino, A. (2013). Ceramics for electronics and energy: issues and opportunities. *Int. J. Appl. Ceram. Technol.* 10 (5): 723–730.

45 Nogawa, H., Hirao, A., Nishimura, Y. et al. *High Power IGBT Module with New AlN Substrate*, 1–8. VDE.

46 Guo, Q., Li, F., Xia, F. et al. (2021). Piezoelectric ceramics with high piezoelectricity and broad temperature usage range. *J. Mater.* 7 (4): 683–692.

47 Pohanka, R.C. and Smith, P.L. (2020). Recent advances in piezoelectric ceramics. *Electron. Ceram.* 45–145.

48 Hamza, M., Kanwal, Q., Hussain, M.I. et al. (2025). Recent progress in 3D printed piezoelectric materials for biomedical applications. *Mater. Sci. Eng. R. Rep.* 164: 100962.

49 Lim, Y., Park, J., Lee, H. et al. (2021). Rapid fabrication of lanthanum strontium cobalt ferrite (LSCF) with suppression of LSCF/YSZ chemical side reaction via flash light sintering for SOFCs. *Nano Energy* 90: 106524.

50 Chen, S.-P., Lv, D., Chen, J. et al. (2022). Review on defects and modification methods of $LiFePO_4$ cathode material for lithium-ion batteries. *Energy Fuel* 36 (3): 1232–1251.

51 Lin, X., Gong, H., and Chen, Z. (2023). Fabrication of SiCN (Fe)/Al_2O_3 wave-absorbing ceramics with enhanced electromagnetic performance. *Ceram. Int.* 49 (14): 23851–23863.

52 Lin, X., Long, Z., Jiang, L. et al. (2023). 3D printed crack-free SiOC (Fe) structures with pyrolysis-induced carbon nanowires for enhanced wave absorption performance. *Ceram. Int.* 49 (20): 33205–33213.

53 Kasana, R., Rathore, P., Shashikumar, U., and Chawla, S. (2024). Nanoceramics: fabrication, properties, and applications. *Ind. Appl. Nanoceram.* 19–36.

54 Thakur, A. and Kumar, A. (2023). *Self-Healing Ceramic Coatings, Advanced Ceramic Coatings for Emerging Applications*, 19–42. Elsevier.

55 Kuznetsova, Y.V. and Popov, I.D. (2022). Design and technological aspects of novel CdS quantum dots doped glass–ceramics. *Ceram. Int.* 48 (13): 18972–18982.

56 Khan, K., Hussain, M.I., Tareen, A.K. et al. (2026). Advances in vat photopolymerization 3D printing: multifunctional materials, process innovations, and emerging applications. *Mater. Sci. Eng. R. Rep.* 167: 101120.

57 Chen, Z., Li, Z., Li, J. et al. (2019). 3D printing of ceramics: a review. *J. Eur. Ceram. Soc.* 39 (4): 661–687.

58 Rasaki, S.A., Xiong, D., Xiong, S. et al. (2021). Photopolymerization-based additive manufacturing of ceramics: a systematic review. *J. Adv. Ceram.* 10 (3): 442–471.

59 Asghar, A., Khan, K., Rashid, M.S. et al. (2025). Extrusion-based additive manufacturing of carbonaceous and non-carbonaceous electrode materials for electrochemical energy storage devices. *Adv. Mater. Technol.* 10: 2400136.

60 Idrees, M., Batool, S., Din, M.A.U. et al. (2023). Material-structure-property integrated additive manufacturing of batteries. *Nano Energy* 109: 108247.

61 ISO/ASTM, ISO/ASTM 52900 (2021). Additive Manufacturing — General Principles — Terminology, 2021.

62 Chaudhary, R.P., Parameswaran, C., Idrees, M. et al. (2022). Additive manufacturing of polymer-derived ceramics: Materials, technologies, properties and potential applications. *Prog. Mater. Sci.* 128: 100969.

63 Hull, C.W. (1986). Methods and apparatus for production of three-dimensional objects by stereolithography. U.S. Patent (Ed.), USA.

64 Griffith, M.L. and Halloran, J.W. (1996). Freeform fabrication of ceramics via stereolithography. *J. Am. Ceram. Soc.* 79 (10): 2601–2608.

65 Nakamoto, T. and Yamaguchi, K. (1996). *Consideration on the Producing of High Aspect Ratio Micro Parts Using UV Sensitive Photopolymer, the Seventh International Symposium of Micro Machine and Human Science*, US, IEEE, pp. 53–58. Nagoya, Japan, October 2–4, 1996.

66 Choi, J.-W., Wicker, R., Lee, S.-H. et al. (2009). Fabrication of 3D biocompatible/biodegradable micro-scaffolds using dynamic mask projection microstereolithography. *J. Mater. Process. Technol.* 209 (15–16): 5494–5503.

67 Maruo, S., Nakamura, O., and Kawata, S. (1997). Three-dimensional microfabrication with two-photon-absorbed photopolymerization. *Opt. Lett.* 22 (2): 132–134.

68 Pham, T.A., Kim, D.P., Lim, T.W. et al. (2006). Three-dimensional SiCN ceramic microstructures via nano-stereolithography of inorganic polymer photoresists. *Adv. Funct. Mater.* 16 (9): 1235–1241.

69 Shusteff, M., Browar, A.E.M., Kelly, B.E. et al. (2017). One-step volumetric additive manufacturing of complex polymer structures. *Science* 3 (12): eaao5496.

70 Kollep, M., Konstantinou, G., Madrid-Wolff, J. et al. (2022). Tomographic volumetric additive manufacturing of silicon oxycarbide ceramics. *Adv. Eng. Mater.* 24: 2101345.

71 Cesarano, I. and Segalman, R. (1998). Robocasting provides moldless fabrication from slurry deposition. *Ceram. Ind.* 148 (4): 94–100.

72 Tuttle, B.A., Smay, J.E., Cesarano, J. et al. (2001). Robocast $Pb(Zr_{0.95}Ti_{0.05})O_3$ ceramic monoliths and composites. *J. Am. Ceram. Soc.* 84 (4): 872–874.

73 Crump, S.S. (1992). Apparatus and method for creating three-dimensional objects, Google Patents.

74 Danforth, S. (1995). Fused deposition of ceramics: a new technique for the rapid fabrication of ceramic components. *Mater. Technol.* 10 (7–8): 144–146.

75 Le, H.P. (1998). Progress and trends in ink-jet printing technology. *J. Imaging Sci. Technol.* 42 (1): 49–62.

76 Blazdell, P., Evans, J., Edirisinghe, M. et al. (1995). The computer aided manufacture of ceramics using multilayer jet printing. *J. Mater. Sci. Lett.* 14 (22): 1562–1565.

77 Sachs, E.M., Haggerty, J.S., Cima, M.J., and Williams, P.A. (1993). Three-dimensional printing techniques, USA. US5204055A.

78 Sachs, E., Cima, M., and Cornie, J. (1990). Three-dimensional printing: rapid tooling and prototypes directly from a CAD model. *CIRP Ann. Manuf. Technol.* 39 (1): 201–204.

79 Deckard, C.R. (1989). Method and apparatus for producing parts by selective sintering, Google Patents.

80 Lakshminarayan, U., Ogrydiziak, S., and Marcus, H. (1990). Selective laser sintering of ceramic materials. *1990 International Solid Freeform Fabrication Symposium*. Austin, TX, USA, August 6–8 1990.

81 Schleifenbaum, H., Meiners, W., Wissenbach, K., and Hinke, C. (2010). Individualized production by means of high power selective laser melting. *CIRP J. Manuf. Sci. Technol.* 2 (3): 161–169.

82 Harlan, N., Park, S.-M., Bourell, D.L., and Beaman, J.J. (1999). Selective laser sintering of zirconia with micro-scale features. *Proc. SFF Symp.*, Austin, pp. 297–302. Austin, TX, USA, August 9–11, 1999.

83 Klocke, F. and Wirtz, H. (1998). Selective laser sintering of zirconium silicate. *Proceedings of Solid Freeform Fabrication*, Austin, Texas. Austin, TX, USA, August 10–12, 1998.

84 Kunieda, M. and Nakagawa, T. (1984). Manufacturing of laminated deep drawing dies by laser beam cutting. *Adv. Technol. Plast.* 1: 520–525.

85 Griffin, C., Daufenbach, J., and McMillin, S. (1994). Desktop manufacturing: LOM vs. pressing. *Am. Ceram. Soc. Bull.* 73 (8): 109–113.

86 Griffith, M., Keicher, D., Atwood, C. et al. (1996). Free form fabrication of metallic components using laser engineered net shaping (LENS). *Solid Freeform Fabrication Proceedings, Proc. 1996 Solid Freeform Fabrication Symposium*, Austin, pp. 125–131.

87 Balla, V.K., Bose, S., and Bandyopadhyay, A. (2008). Processing of bulk alumina ceramics using laser engineered net shaping. *Int. J. Appl. Ceram. Technol.* 5 (3): 234–242.