SHEng
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3D printing technologies and materials for medical applications

Class content material

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The collection is intended for engineering students and professionals working in the healthcare sector. It covers technical subjects relevant to hospital infrastructure, equipment, materials and support services, helping readers understand how engineering contributes to safe patient care and the reliable operation of healthcare facilities.

These materials support classroom teaching and independent study. They should be used alongside the project handbook and the presentations, courses and other learning resources available on the project website. Each document addresses a specific subject, while the collection provides a broader understanding of the responsibilities and practical challenges of healthcare engineering.

The content is educational. Its application in practice requires consideration of the conditions of each healthcare facility, the applicable standards and the instructions provided by equipment manufacturers.

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3D printing technologies and materials for medical applications

Additive manufacturing (AM), commonly known as three-dimensional (3D) printing, has emerged as a transformative technology in modern medicine, enabling the fabrication of patient specific medical devices, anatomical models, surgical instruments, implants, prostheses, and tissue-engineering scaffolds. Unlike conventional manufacturing methods, which frequently involve material removal, additive manufacturing enables the layer by layer fabrication of complex structures directly from digital three-dimensional models. This approach offers significant advantages in terms of geometrical complexity, customization, material utilization, and the integration of functional features.

Additive manufacturing represents one of the most significant technological developments in advanced manufacturing, with applications extending from aerospace and automotive engineering to biomedical engineering and personalized medicine. In the medical sector, the increasing demand for individualized treatments, complex implant geometries, and improved surgical planning has accelerated the adoption of three-dimensional printing technologies.

According to the ISO/ASTM 52900 classification, additive manufacturing processes are grouped into seven principal categories based on the mechanisms used to selectively join or consolidate materials:

- ✓ Vat Photopolymerization (VPP);
- ✓ Powder Bed Fusion (PBF);
- ✓ Binder Jetting (BJT/BJ);
- ✓ Material Jetting (MJT/MJ);
- ✓ Material Extrusion (MEX/ME);
- ✓ Directed Energy Deposition (DED);
- ✓ Sheet Lamination (SHL/SL).

AM category	Technologies	Typical medical materials	Representative applications
Material Extrusion (MEX)	FFF, FDM, FGF, DIW	PLA, PCL, PEEK, PEKK, TPU, hydrogels	Anatomical models, orthoses, scaffolds
Vat Photopolymerization (VPP)	SLA, DLP, LCD	Photopolymer resins, ceramic-filled resins	Dental guides, models, temporary restorations
Powder Bed Fusion (PBF)	PBF-LB/M, PBF-EB/M, PBF-LB/P, SLS	Ti-6Al-4V, Co-Cr, PA12, PEEK in specialized systems	Implants, surgical instruments, prosthetic components
Material Jetting (MJT)	PolyJet, inkjet-based printing	Photopolymers, selected bioinks	Anatomical models, surgical planning
Binder Jetting (BJT)	Binder jet printing	Metals, ceramics, calcium phosphates	Porous structures, research scaffolds
Directed Energy Deposition (DED)	DED-LB, DED-Arc	Titanium alloys, Co-Cr alloys	Implant repair, surface modification, research
Sheet Lamination (SHL)	LOM, ultrasonic additive manufacturing	Polymer sheets, metallic foils	Anatomical models, specialized tooling

The most common technologies are material extrusion (MEX), vat photopolymerization (VPP), selective laser sintering (SLS), powder bed fusion (PBF), liquid deposition modelling (LDM).

1. Material Extrusion Technologies for Medical Applications

Material extrusion is among the most accessible and versatile additive manufacturing categories for biomedical applications. In this process, material is selectively deposited through a nozzle following a predefined plain sction.

The most relevant variants include fused filament fabrication (FFF), fused granulate fabrication (FGF), and direct ink writing (DIW).

1.1. Fused Filament Fabrication (FFF)

Consists in depositing a molten material with an extrusion head that traces each layer of the model using a thin plastic thread or wax. The extruded material cools quickly thus, it forms the solid layer. From this system, each layer in accordance with the 3D-CAD model is made on the previous layer, with the remark that the prototype construction starts from the base.

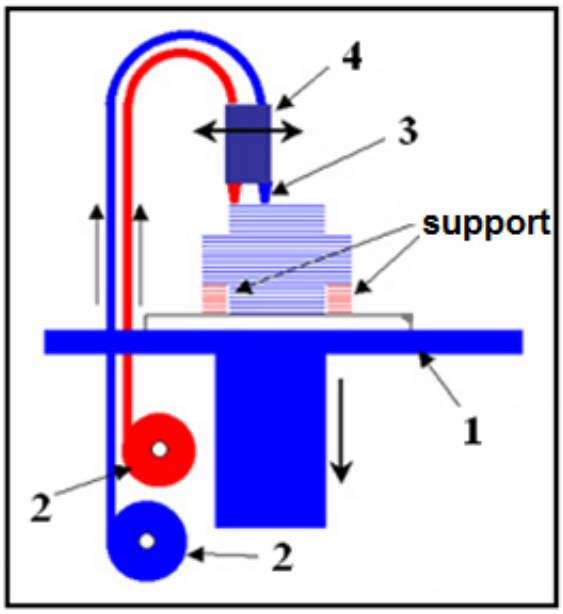

Fig. 1 FFF process: 1 – building tray, 2 - material supply devices, 3 - heated extrusion nozzles, 4 - extrusion head. [1]

The principal advantages of FFF include relatively low equipment costs, compatibility with numerous thermoplastic polymers, controlled internal architectures, and the possibility of producing customized devices.

The most important biomedical polymers include:

- Polylactic acid (PLA). PLA is a biodegradable aliphatic polyester derived from renewable resources. It offers good processability, relatively high stiffness, and suitability for the fabrication of anatomical models, research scaffolds, and selected biodegradable medical applications. However, commercial PLA filaments are not necessarily medical-grade materials. PLA is also relatively brittle and may undergo thermal or hydrolytic degradation during processing and service.

- Polycaprolactone (PCL). PCL is a semicrystalline biodegradable polyester with a relatively low melting temperature, typically around 55–65 °C. Its flexibility, slow degradation, and compatibility with certain tissue-engineering approaches make it particularly attractive for scaffold manufacturing. Its limited stiffness restricts its use in highly loaded structures unless reinforcement or other design measures are employed.
- Polyether ether ketone (PEEK). PEEK is a high performance, semicrystalline thermoplastic characterized by excellent chemical resistance, thermal stability, and mechanical properties. Implant grade PEEK is used in certain orthopedic and spinal applications. Its processing generally requires high nozzle temperatures and carefully controlled chamber conditions. Its relatively bioinert surface may require modification to improve bone integration.
- Polyether ketone ketone (PEKK). PEKK belongs to the polyaryletherketone family and provides high thermal stability, chemical resistance, and attractive mechanical characteristics. Its crystallization behaviours can offer processing advantages for certain high temperature AM systems. Medical applications remain dependent on the qualification of the specific formulation and process.
- Thermoplastic polyurethane (TPU). TPU is an elastomeric material with adjustable flexibility, elasticity, and wear characteristics. Selected grades can be employed in orthotic devices, prosthetic components, flexible anatomical models.
- Polypropylene (PP). PP is a lightweight, chemically resistant thermoplastic used in conventional medical products. In additive manufacturing, its application is limited by shrinkage, warpage, and interlayer adhesion challenges. Qualified formulations may be suitable for external medical components and selected device applications.

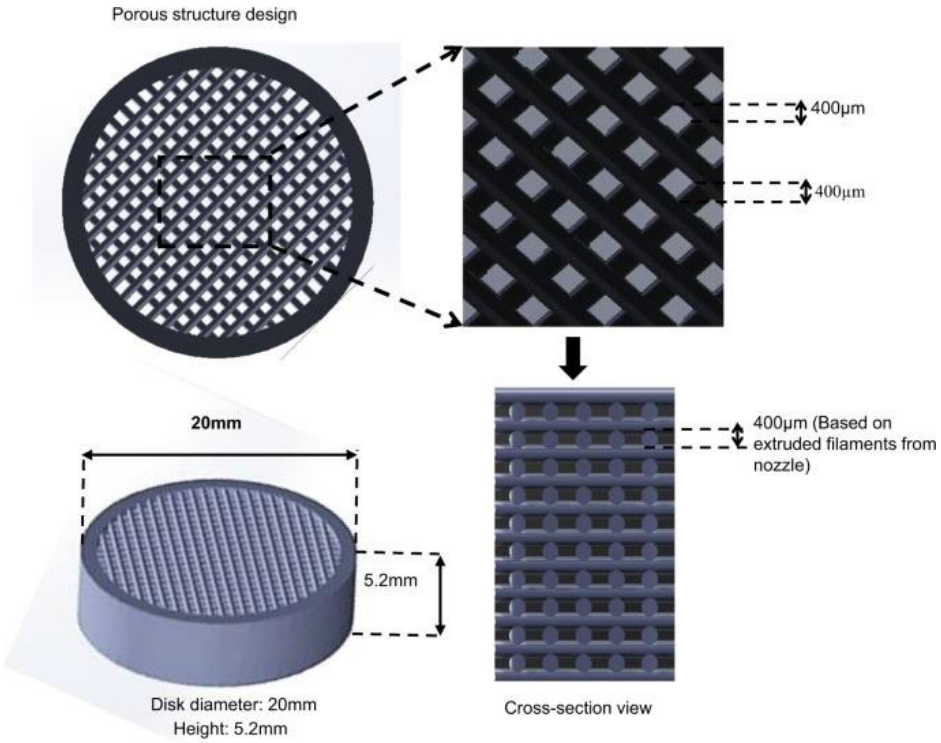

Fig. 1.2 Porous structures [2]

2. Vat photopolymerization (VPP)

Vat photopolymerization is based on the selective curing of liquid photopolymer resins using light. Its main variants are stereolithography (SLA), digital light processing (DLP), and LCD-based masked stereolithography (MSLA).

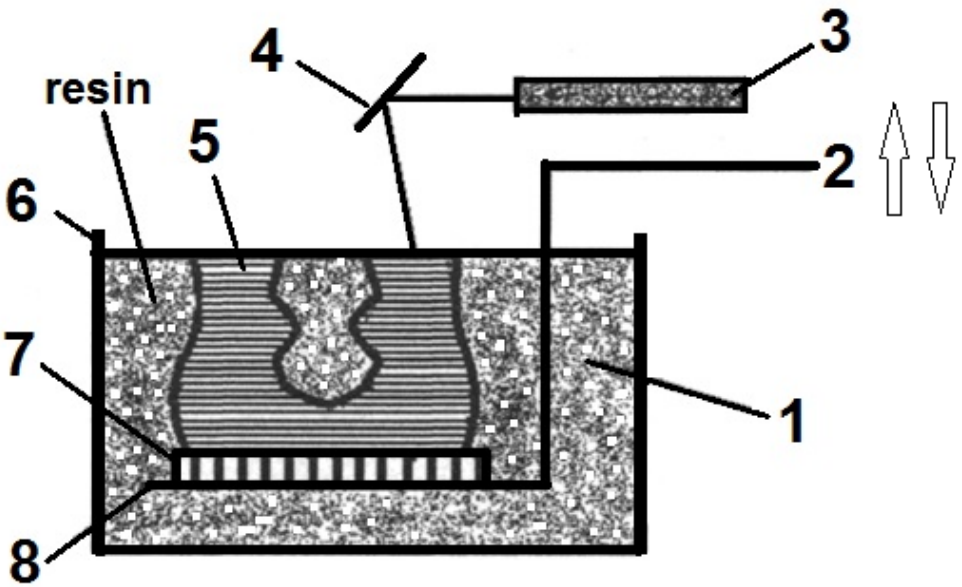

Fig. 2.1 SLA - stereolithography: 1 - liquid resin; 2 - model stand; 3 - laser scanning system; 4 - mirror; 5 - solid model made by polymerizing the resin; 6 – the chamber with liquid resin; 7 - stand/ base plate for the model ; 8 - vertical displacement system. [1]

Photopolymer Materials

- The principal materials include acrylate and methacrylate based resins, urethane acrylates, epoxy based systems, and specialized dental resin formulations.
- Applications include dental surgical guides, orthodontic models, temporary restorations, occlusal splints, hearing-aid shells, and patient specific anatomical models.
- Ceramic filled photopolymer systems can also be used to manufacture ceramic components. Following printing, the organic binder is removed, and the ceramic structure is sintered. Alumina, zirconia, and hydroxyapatite based compositions are among the materials investigated.
- The most significant limitations are residual monomers, incomplete polymerization, photoinitiator related toxicity, dimensional changes during post curing, and degradation of properties under sterilization.
- Consequently, washing and post curing procedures must follow validated protocols, particularly for intraoral or other patient contact applications.

Fig. 2.2 dental implantology training model [4]

3. Selective laser sintering (SLS)

It operates similar to Stereolithography, with the difference that the material used is a fusible powder (plastic, polyamide, ceramic, rubber, polystyrene, steel). Using the laser beam, the 3D-CAD sectioned model is reproduced in layers on the surface of the powders that melt locally. A new layer of powder is brought by the roller onto the print area of the left-right feed bunkers - right over the previously hardened layer, following the sintering of a new layer of the model. The excess of powder is removed after the whole model has been completed.

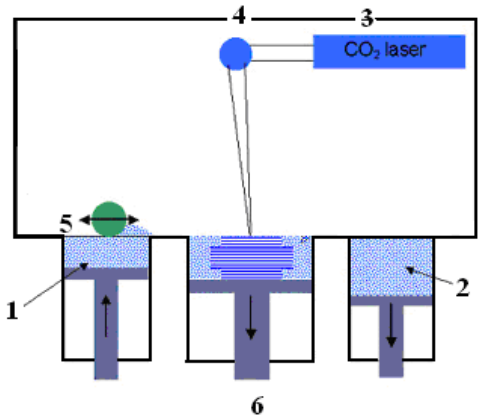

Fig. 3.1 SLS process: 1 – powder supply cartridge; 2 – powder surplus cartridge; 3 - laser scanning system; 4 - optical system; 5 - powder dosing device; 6 - vertical displacement platform. [1]

Common materials include polyamide 12 (PA12), polyamide 11 (PA11), and selected specialized engineering polymers.

Medical applications include external prosthetic components, orthoses, anatomical models, and customized rehabilitation devices.

SLS offers considerable design freedom and generally does not require conventional support structures. However, powder aging, surface roughness, porosity, and cleaning of residual powder must be considered.

4. Powder bed fusion (PBF)

Powder bed fusion selectively consolidates successive layers of powdered material using a thermal energy source. It is one of the most important industrial AM categories for manufacturing high-performance medical implants.

Fig. 4.1 Porous metallic acetabular cups [3]

The most relevant metallic materials include:

- Titanium and titanium alloys. Commercially pure titanium and Ti-6Al-4V are extensively used for medical implants because of their corrosion resistance, strength, and established clinical history. Ti-6Al-4V ELI is particularly relevant to implant applications. Titanium lattice structures can reduce effective structural stiffness and facilitate bone ingrowth.
- Cobalt-chromium alloys. Co-Cr alloys exhibit high strength, wear resistance, and corrosion resistance. They are used in selected dental frameworks and orthopedic applications. Their processing requires careful control of composition, microstructure, surface condition, and potential ion release.
- Stainless steel 316L. This alloy offers good corrosion resistance and processability. Although 316L has medical applications, not every additively manufactured 316L component is suitable for permanent implantation. Its intended use, material specification, and corrosion performance must be established.
- Tantalum. Tantalum has attracted interest for highly porous orthopedic structures because of its corrosion resistance and favourable biological interactions. Its high density and processing cost remain disadvantages.

Representative polymeric materials for medical additive manufacturing

Material	Main characteristics	Compatible AM processes	Typical applications
PLA	Biodegradable, relatively stiff, processable	FFF, FGF	Models, experimental scaffolds
PCL	Biodegradable, flexible, slow degradation	FFF, DIW, FGF	Tissue-engineering scaffolds
PLGA	Degradation through copolymer composition	Specialized extrusion, printing formulations	Drug delivery, resorbable scaffolds
PEEK	High-performance, chemically resistant	High-temperature FFF, specialized PBF	Selected spinal and orthopedic implants
PEKK	High thermal resistance, adjustable crystallization	High-temperature FFF, specialized PBF	Research implants, surgical components
TPU	Flexible, elastic, abrasion-resistant	FFF, SLS for suitable grades	Orthoses, prosthetic components
PA12	Tough, good fatigue performance	SLS, MJF	Orthoses, external medical devices
PMMA	Rigid, optically useful in suitable forms	Specialized resin and material systems	Dental and anatomical applications
Silicone	Elastomeric, flexible	Specialized extrusion and jetting	Prosthetic and anatomical models

The table identifies representative material-process combinations; it does not imply that every commercially available grade is medically certified.

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Acknowledgments

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