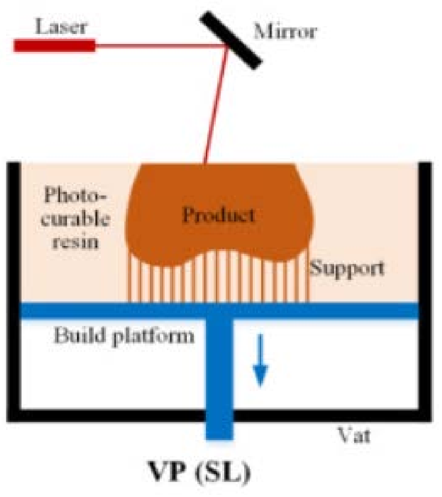
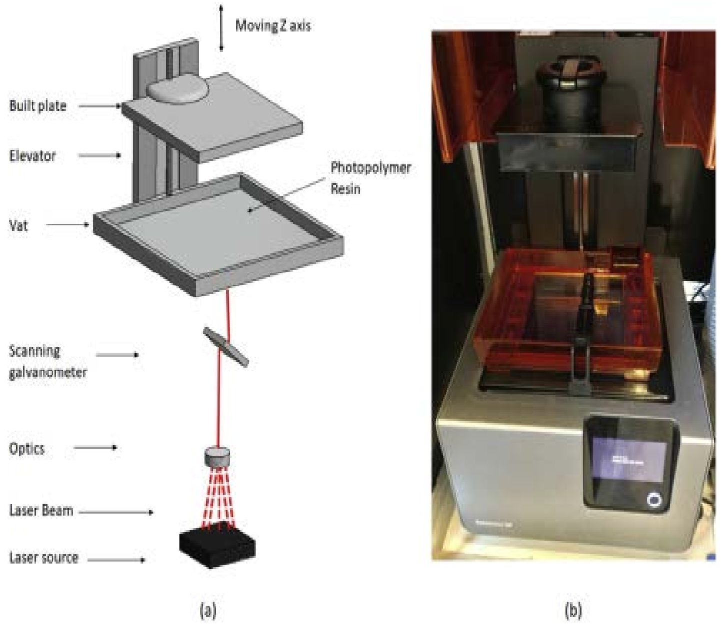
Ceramics Fabrication Techniques



❖ **Vat photopolymerization (VP):** It is a high-precision 3D printing method for ceramic dental restorations, using light to cure a ceramic–photopolymer slurry layer-by-layer, followed by cleaning, debinding, and sintering. SLA offers point-by-point laser accuracy, while DLP cures entire layers faster. VP enables complex, smooth, and accurate parts in zirconia, alumina, and glass-ceramics, achieving over 98% density and clinical-grade strength, though it involves long post-processing, high costs, and sensitivity to light scattering. It is widely used for crowns, bridges, veneers, implants, and abutments.

Main two types

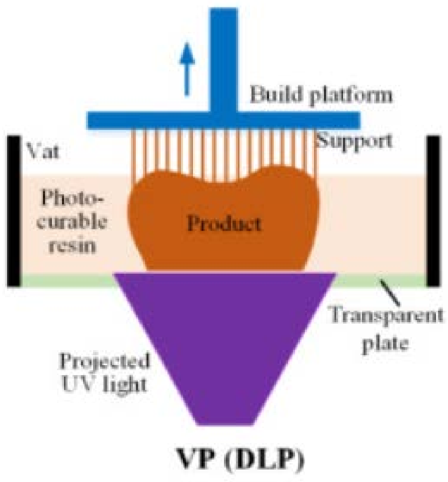


1.Stereolithography (SL / SLA)

Uses a *focused laser beam* (355 or 405 nm).Cures point-by-point by scanning each layer.

Advantage: Very high resolution (~40 μm, even 25 μm in advanced systems).

Drawback: Slower than DLP.



2.Digital Light Processing (DLP)

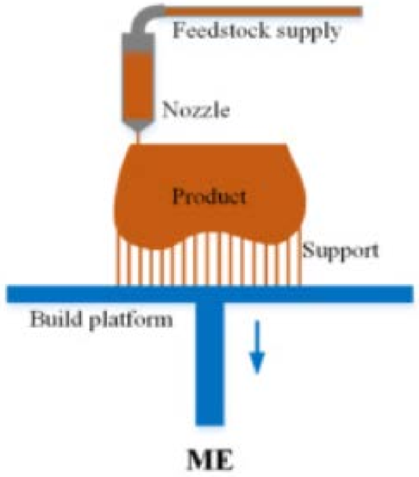
Uses a *projector* with UV/visible light (365, 405, or 460 nm).Cures entire layer at once using a digital micromirror device (DMD)

Advantage: Faster than SL; high accuracy.

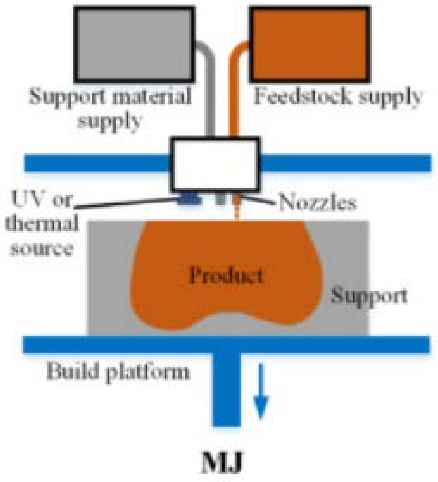
https://www.sciencedirect.com/topics/engineering/stereolithography-machine

https://doi.org/10.1016/j.jmrt.2023.07.257

Ceramics Fabrication Techniques

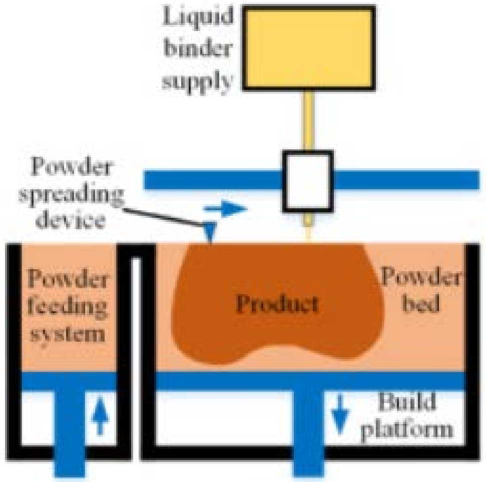


- **Material extrusion (ME):** is a 3D printing method where a viscoelastic ceramic paste or ink is selectively dispensed through a nozzle to build parts layer-by-layer, followed by support removal, debinding, and sintering. Common variants include robocasting (RC) and direct ink writing (DIW). The ceramic ink must have high solid loading, smooth extrusion, and the ability to hold its shape after deposition, with rheological properties tuned by particle size, solid content, and additives. ME is low-cost, versatile, and suitable for multi-material structures, but has lower accuracy, slower speed, rougher surfaces, and risks of nozzle clogging compared to vat photopolymerization. It is mainly used with zirconia and alumina for crowns, bridges, and prototypes, achieving densities up to ~98.5% and flexural strengths over 500 MPa when optimized, though surface roughness remains higher than with VP methods.

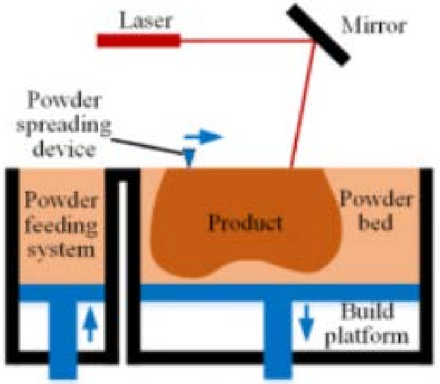


- **Material jetting (MJ):** is a high-resolution 3D printing process that deposits and cures tiny droplets of ceramic ink layer-by-layer, enabling fine features, multi-material printing, and layer thicknesses as low as 10 μm. It typically uses zirconia suspensions with 20–30 vol% solids, though advanced nanoparticle jetting (NPJ) can achieve >99% density and smooth surfaces. While suitable for crowns, bridges, and implant abutments with high accuracy, MJ is slower, prone to nozzle clogging, and less common than vat photopolymerization in ceramic dental applications.

Ceramics Fabrication Techniques



BJ



PBF

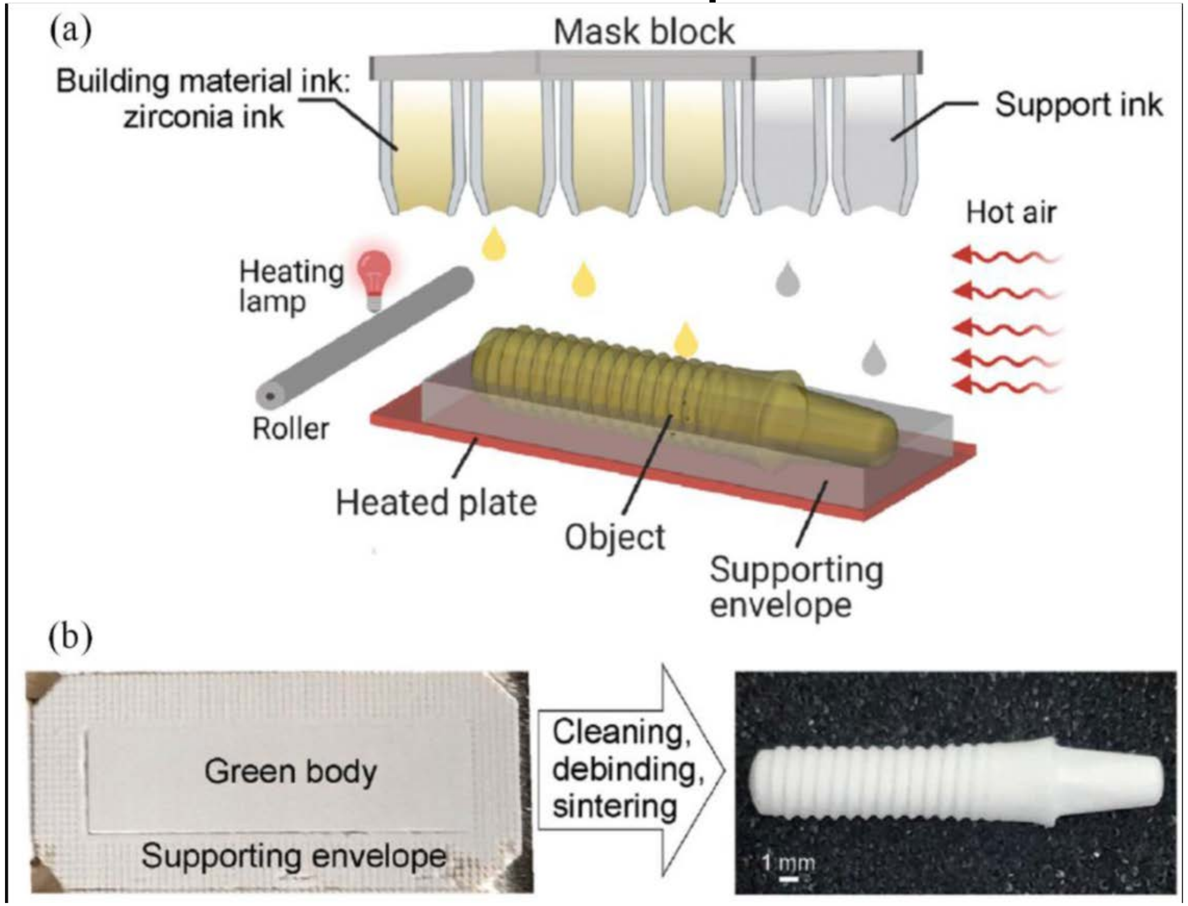
- **Binder jetting (BJ):** is a powder-bed 3D printing process where a liquid binder selectively bonds ceramic powder layers, followed by curing, depowdering, debinding, and sintering. It works with zirconia, alumina, and glass-ceramics, offering low cost and no support structures, but typically yields lower density, strength, and accuracy than vat photopolymerization. In dentistry, BJ has been tested for crowns and bridges but remains limited due to performance constraints.

- **Powder bed fusion (PBF):** is a laser- or electron beam-based 3D printing process that selectively fuses ceramic powders layer-by-layer using thermal energy. The two main variants are **selective laser melting (SLM)**, which directly melts the ceramic, and **selective laser sintering (SLS)**, which fuses powder via a binder phase that is later removed. PBF can create complex shapes without support structures and has high efficiency, but ceramics pose challenges due to high melting points, low laser absorption, and brittleness, often causing cracks, poor surface quality, and low dimensional accuracy. Techniques like adding absorbers or preheating can improve density (up to ~97%), yet mechanical properties often remain inferior to those from vat photopolymerization. In dental applications, PBF has been explored for zirconia and alumina bridges, crowns, and composite restorations, but adoption is limited due to quality and reliability issues.

https://doi.org/10.1016/j.jmrt.2023.07.257

Ceramics

❖ **Ceramics Fabrication Techniques**



Schematic illustrating the NPJ process. (b) Top view of a printed part illustrating the green body and post-treated implant

(a) Printing Process

- ❑ **Mask block:** Contains multiple nozzles that deposit two types of ink — **building material ink** (zirconia ink) and **support ink** — in specific regions.
- ❑ **Deposition:** Droplets of zirconia ink form the actual object, while support ink forms the surrounding support structure (supporting envelope).
- ❑ **Heating system:**
- ❑ **Hot air** and a **heating lamp** assist in evaporating the solvent quickly after deposition.
- ❑ A **roller** helps level the layer.
- ❑ A **heated plate** beneath the build area further promotes solvent evaporation and layer solidification.
- ❑ **Layer-by-layer building:** The object grows as each layer is deposited and dried before the next one.

Part **(b)** shows the post-processing stage, where the printed zirconia **green body** enclosed in a supporting envelope is cleaned, the envelope removed, then debound and sintered to form the final dense ceramic part.

Ceramics

❖ **Ceramics Fabrication Techniques**

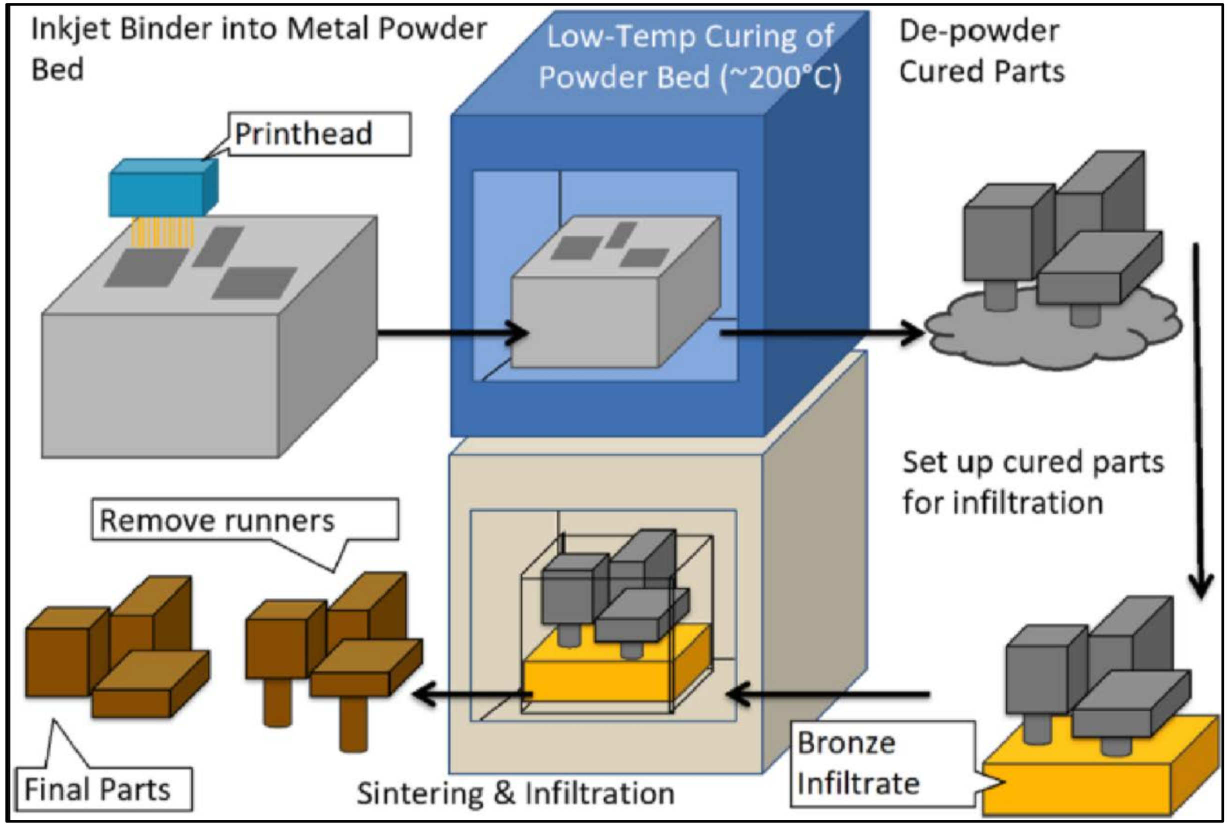


Illustration of binder jet 3D printed parts followed by curing, depowdering, and densification (infiltration) steps

An **inkjet printhead** selectively deposits a liquid binder into a bed of **metal powder** (often stainless steel).This binds powder particles together layer-by-layer, forming "green" parts inside the loose powder bed.

Low-Temperature Curing (~200 °C) The entire powder bed is heated at a relatively low temperature to harden the binder and stabilize the parts.

Depowdering Loose powder surrounding the parts is removed, revealing the **cured green parts**.

Preparation for Infiltration The cured parts are positioned in a furnace setup along with bronze material (infiltrant).

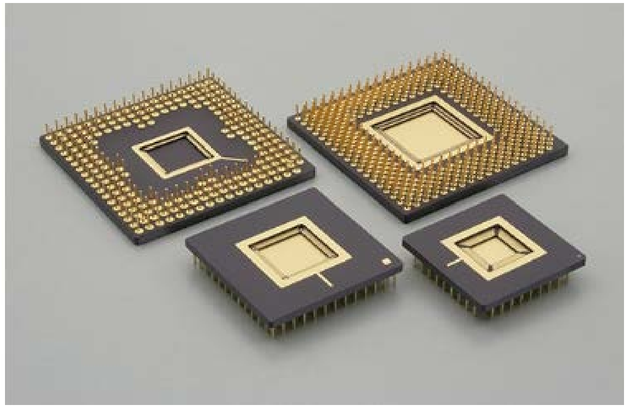
Sintering & Infiltration During heating, the steel particles partially sinter, and molten bronze infiltrates the pores by capillary action.

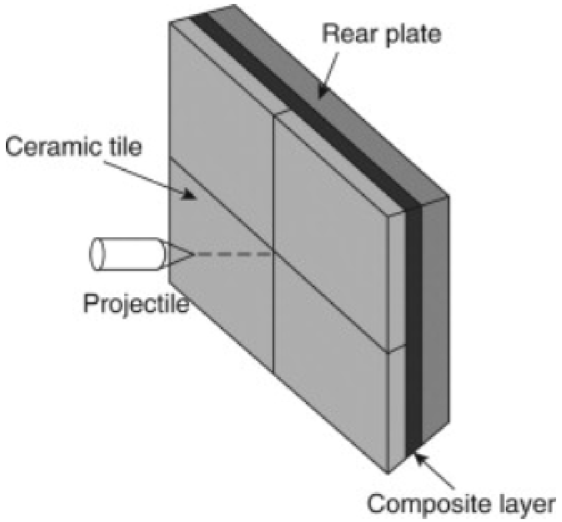
This fills the voids, increasing density and mechanical strength.

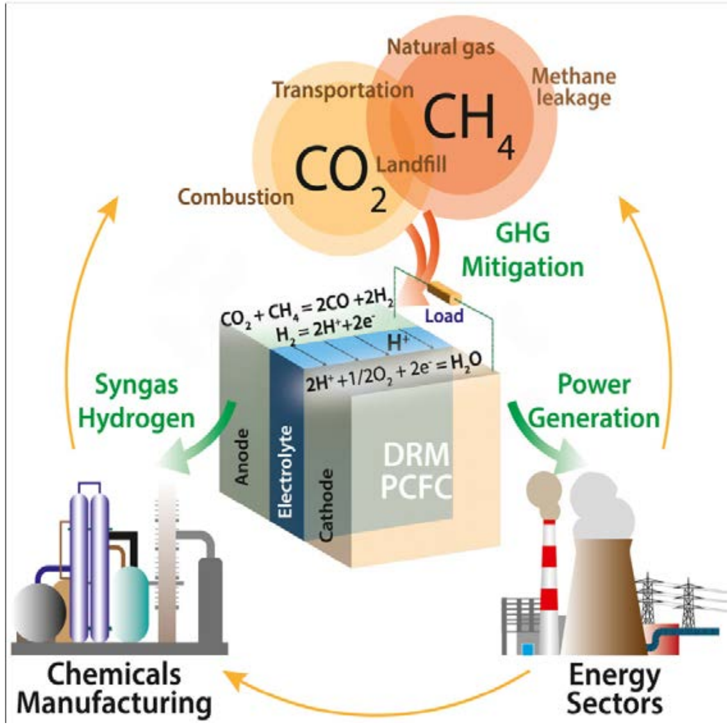
Removing Runners Excess infiltration channels or supports ("runners") are removed.

Final Parts Fully dense, strong metal components are obtained, suitable for functional use.

Ceramics







❖ **Applications**

- ❑ **Aerospace**: Turbine blades, nose cones
- ❑ **Biomedical**: Dental crowns, bone scaffolds
- ❑ **Electronics**: Substrates, sensors, insulators
- ❑ **Energy**: Fuel cells, thermal barrier coatings
- ❑ **Armor**: Bulletproof plates (e.g., boron carbide)

❖ **Challenges**

- ❑ Brittleness limits design flexibility.
- ❑ Difficulties in machining and joining.
- ❑ Requires high-temperature processing and precise control over microstructure.

Difference between Glass & Ceramics

Property	Glass	Ceramic
Atomic Structure	Amorphous (non-crystalline)	Crystalline (can be partially or fully crystalline)
Formation Process	Rapid cooling of melt to prevent crystallization	High-temperature sintering of powders or slurries
Bonding Type	Mainly covalent with some ionic character	Mostly ionic or covalent bonds
Appearance	Usually transparent	Usually opaque (can be translucent or white)
Mechanical Properties	Hard, brittle; low fracture toughness	Very hard and stiff, but often brittle; improved with toughening methods
Thermal Properties	Low thermal conductivity; softens gradually	High thermal stability; some ceramics withstand >2000°C
Electrical Properties	Good insulator; some are optoelectronic (e.g., optical fibers)	Typically insulating; some are semiconductors or superconductors
Processing Techniques	Float process, blowing, molding, laser/nanoimprint lithography	Sintering, hot pressing, spark plasma sintering, additive manufacturing
Fracture Behavior	Brittle failure; low crack resistance	Brittle, but some ceramics are engineered to have high fracture toughness
Applications	Windows, displays, optics, solar panels, bio-glass, nuclear vitrification	Armor, cutting tools, dental implants, fuel cells, aerospace components
Special Forms	Glass-ceramics, photochromic, electrochromic, bioactive glass	Oxide, non-oxide, nanostructured, bioinspired ceramics
Temperature Response	Viscosity changes gradually with temperature	Sharp phase transitions; retains shape until melting point
Machinability	Difficult (can fracture easily)	Very difficult; requires precision grinding or advanced machining
Examples	Soda-lime glass, borosilicate glass, metallic glass	Alumina, zirconia, silicon carbide, boron nitride

Materials and Design 32 **(2011)** 1717–1732 https://doi.org/10.1016/j.jmrt.2023.07.257

Introduction to Refractory

Refractory

What Are Refractory Materials?

❖ **Definition**

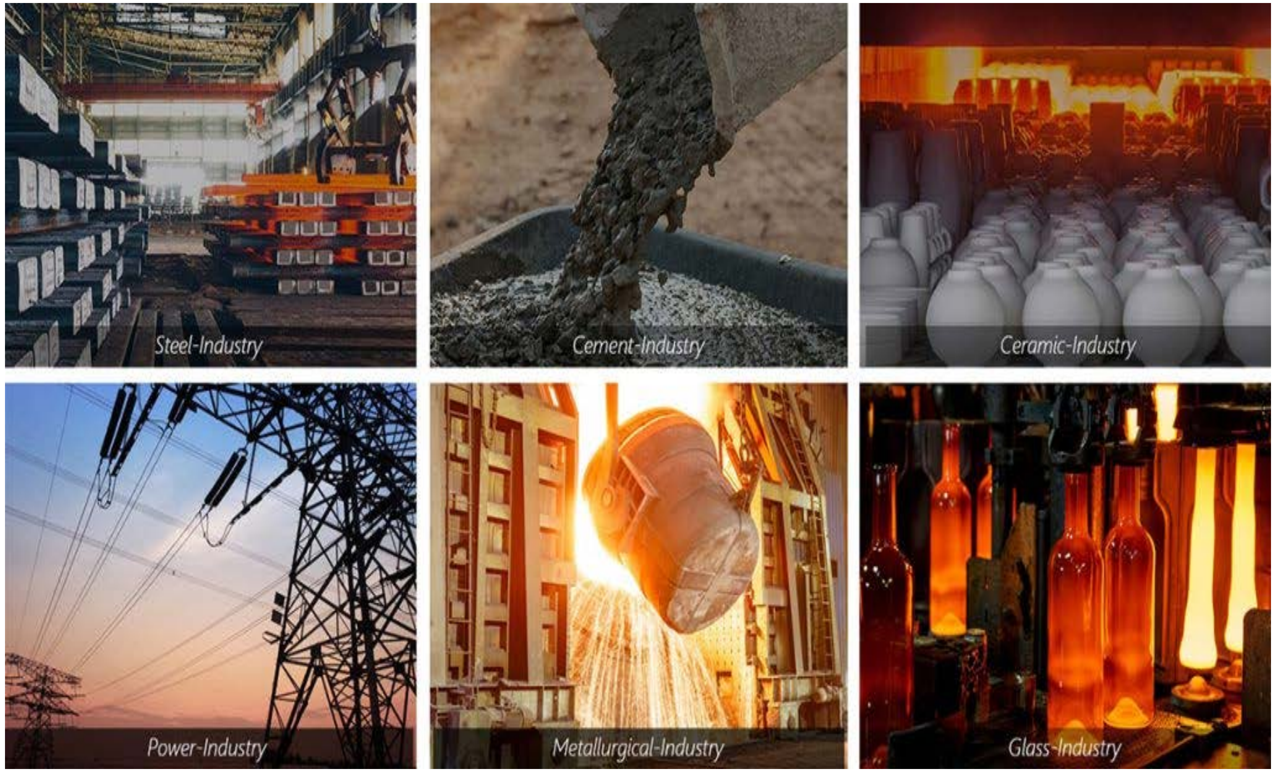
- ❑ Refractories are materials that retain their strength and chemical integrity at high temperatures.
- ❑ Typically used in thermal, chemical, nuclear, and structural environments exceeding 1500 °C.
- ❑ Exhibit resistance to thermal shock, corrosion, and radiation damage.

❖ **Key Properties Required in Refractory Materials**

- ❑ Low thermal expansion
- ❑ High thermal conductivity
- ❑ Low activation (for fusion) – to reduce radioactive waste
- ❑ Resistance to helium blistering and swelling under irradiation
- ❑ Compatibility with coolants (e.g., helium, liquid metals)

https://doi.org/10.1016/B978-0-12-397046-6.00013-7

Application of Refractory



- **Metallurgy:** Furnace linings, crucibles, and molds for metal processing.
- **Glass Industry:** Glass melting furnace linings.
- **Cement Industry:** Rotary kiln linings.
- **Power Plants:** Boiler and incinerator linings.
- **Petrochemical:** Reactor and reformer linings.
- **Ceramics:** Kiln linings for firing ceramics.
- **Others:** Heat shields, fireproofing, and insulation in aerospace, automotive, and construction.

https://www.rsnewrefractory.com/application/refractory-application-industry/ https://doi.org/10.1016/B978-0-12-397046-6.00013-7

Comparison Table: Glass vs Ceramic vs Refractory

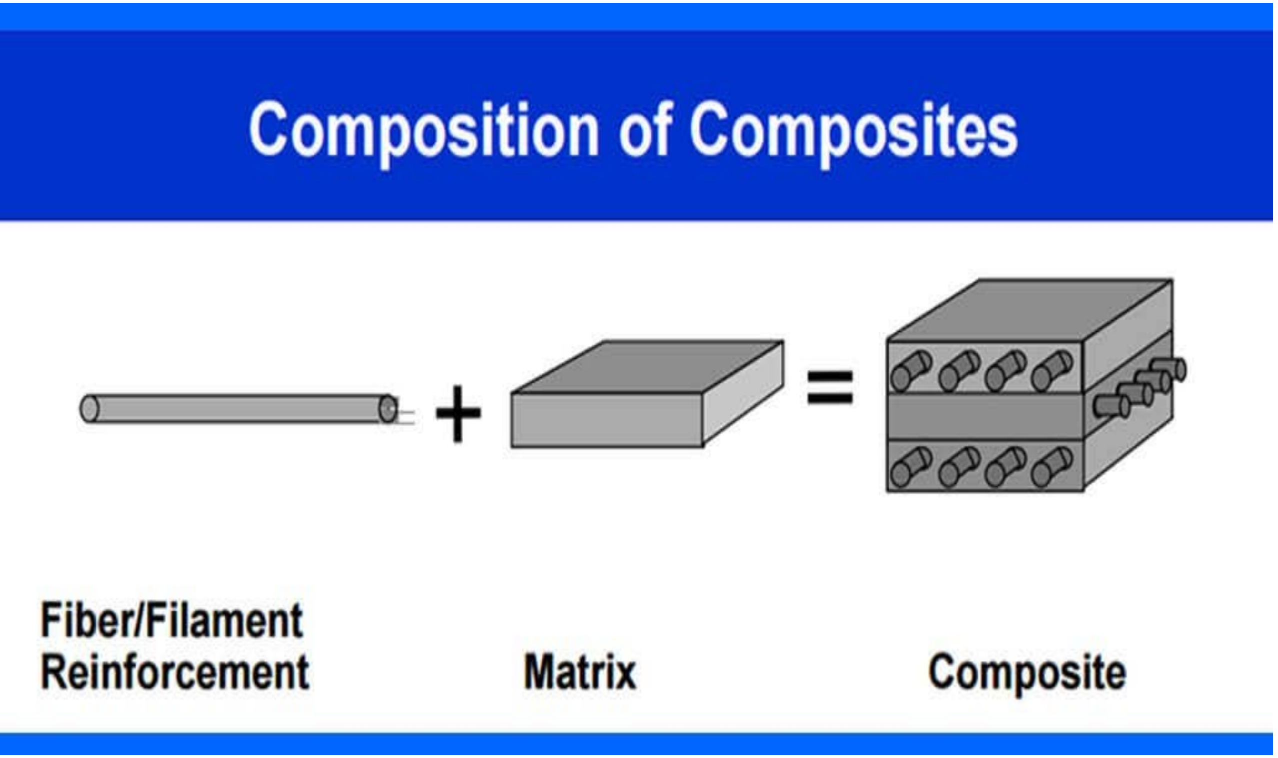
Property	Glass	Ceramic	Refractory
Structure	Amorphous (non-crystalline)	Crystalline or partially crystalline	Mostly crystalline or composite structures
Composition	Silica-based with modifiers (Na_2O, CaO)	Metal oxides, carbides, nitrides, borides	Ultra-high-temp oxides, carbides, borides, refractory metals (e.g., W, Mo)
Thermal Stability	Moderate (up to 700°C typically)	High (1000–1600°C)	Very High (up to and beyond 3000°C)
Melting Point	~600–1500°C	~1000–2000°C	>2000°C (W: 3422°C, HfC: ~3900°C)
Mechanical Strength	Moderate; brittle	High hardness; brittle	High strength; retains toughness at extreme temperatures
Electrical Properties	Insulators or optoelectronic materials	Insulators, semiconductors, superconductors	Usually insulating or semiconducting; some metallic
Thermal Conductivity	Low	Moderate to high (SiC, AlN are high)	High (esp. SiC, W, ZrC) to manage extreme heat loads
Transparency	Usually transparent	Opaque or translucent	Opaque
Fracture Toughness	Low	Low to moderate; improved in toughened ceramics	Moderate to high (some are toughened or fiber-reinforced)
Applications	Windows, optics, displays, solar panels	Cutting tools, armor, dental implants, electronics	Nuclear reactors, kilns, furnaces, hypersonic vehicles, plasma-facing components
Radiation Tolerance	Poor to moderate	Good (SiC, Al_2O_3)	Excellent (e.g., W, SiC/SiC composites in fusion)
Thermal Shock Resistance	Poor to moderate	Moderate; can be enhanced	Excellent in some (e.g., ZrB_2, SiC)
Examples	Soda-lime glass, borosilicate, metallic glass	Alumina, zirconia, silicon carbide, glass-ceramics	Tungsten, molybdenum, hafnium carbide, SiC/SiC composites

https://doi.org/10.1016/B978-0-12-397046-6.00013-7

Introduction to composites

Composites

What Are Composite Materials?



- **Composite materials** are engineered by combining two or more distinct constituents (typically a matrix and reinforcement) to produce a material with superior properties that are not attainable by the individual components alone.

- **Matrix**: Binds the reinforcement and transfers loads (e.g., polymers, metals, ceramics).

- **Reinforcement**: Provides strength and stiffness (e.g., fibers like carbon, glass, or aramid).

- Historically, composites have evolved from ancient straw-reinforced mud bricks to modern **carbon fiber-reinforced polymers (CFRPs)** and **ceramic matrix composites (CMCs)** used in aerospace and automotive sectors.

Composites

❖ Types of Composite Materials

1. **Based on Matrix Material:**

- **Polymer Matrix Composites (PMCs)** – Most common; includes thermosets (epoxy) and thermoplastics (PA6, PP).
- **Metal Matrix Composites (MMCs)** – Metals like aluminum reinforced with SiC, B4C, or carbon fibers.
- **Ceramic Matrix Composites (CMCs)** – Offer high-temperature stability and hardness (e.g., SiC, Al_2O_3).

2. **Based on Reinforcement Form:**

- **Fibre Reinforced Composites**: CFRP, GFRP, AFRP, NFRC.
- **Particle Reinforced Composites**: Al–SiC, used in brake discs.
- **Flake Reinforced Composites**: Use graphite or graphene flakes for improved conductivity.
- **Filler Reinforced Composites**: Use nano/micro fillers to enhance thermal, electrical, or mechanical properties.

3. **Structural Composites:**

- Include **sandwich panels**, **laminates**, and **layered composites**.

Composites

Property	Explanation
➢ **High Strength-to-Weight Ratio**	Carbon fibers can be 15x stronger than steel but at 1/4 the weight.
➢ **Corrosion Resistance**	Ideal for harsh environments (e.g., saltwater, chemicals).
➢ **Durability**	Resistant to fatigue, rust, and temperature changes.
➢ **Impact Resistance**	Suitable for bulletproofing and crash-absorption in vehicles.
➢ **Thermal & Electrical Insulation**	Can be tuned to be insulating or conductive.
➢ **Non-Magnetic**	Suitable for MRI rooms and sensitive electronics.
➢ **Fire and Lightning Resistance**	Advanced composites can withstand fire and offer lightning protection.
➢ **Design Flexibility**	Can be moulded into complex shapes, reducing part count.
➢ **Eco-Friendly Options**	Use of biodegradable or natural fibers for sustainability.

Journal of Engineering Research 13 **(2025)** 1001–1023

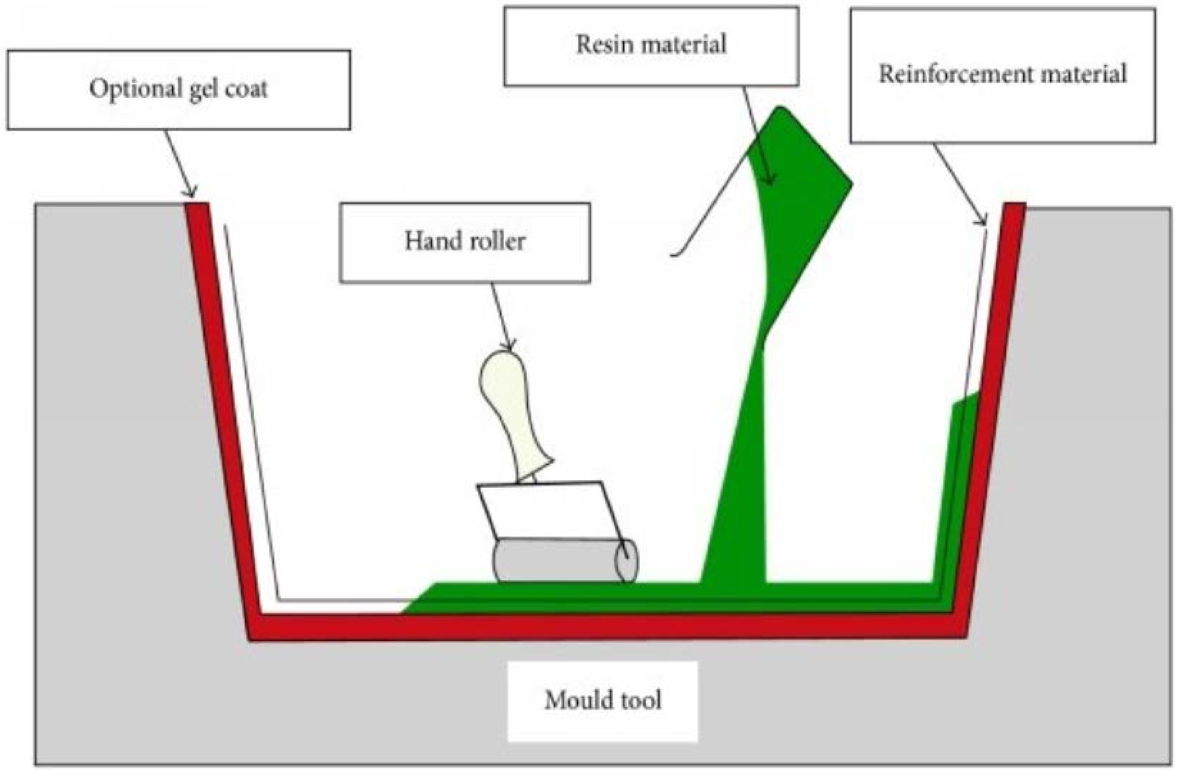
Composites

❖ **Fabrication Techniques**

1. **Hand Lay-Up Technique**
2. **Resin Transfer Moulding (RTM)**
3. **Compression Moulding**
4. **Filament Winding**
5. **Automated Fibre Placement (AFP) / Automated Tape Laying (ATL)**
6. **Vacuum Assisted Resin Transfer Moulding (VARTM)**
7. **Sheet Moulding Compound (SMC) and Bulk Moulding Compound (BMC) Techniques**

Composites

1. Hand Lay-Up Technique



- **Description**: One of the simplest and oldest fabrication methods.

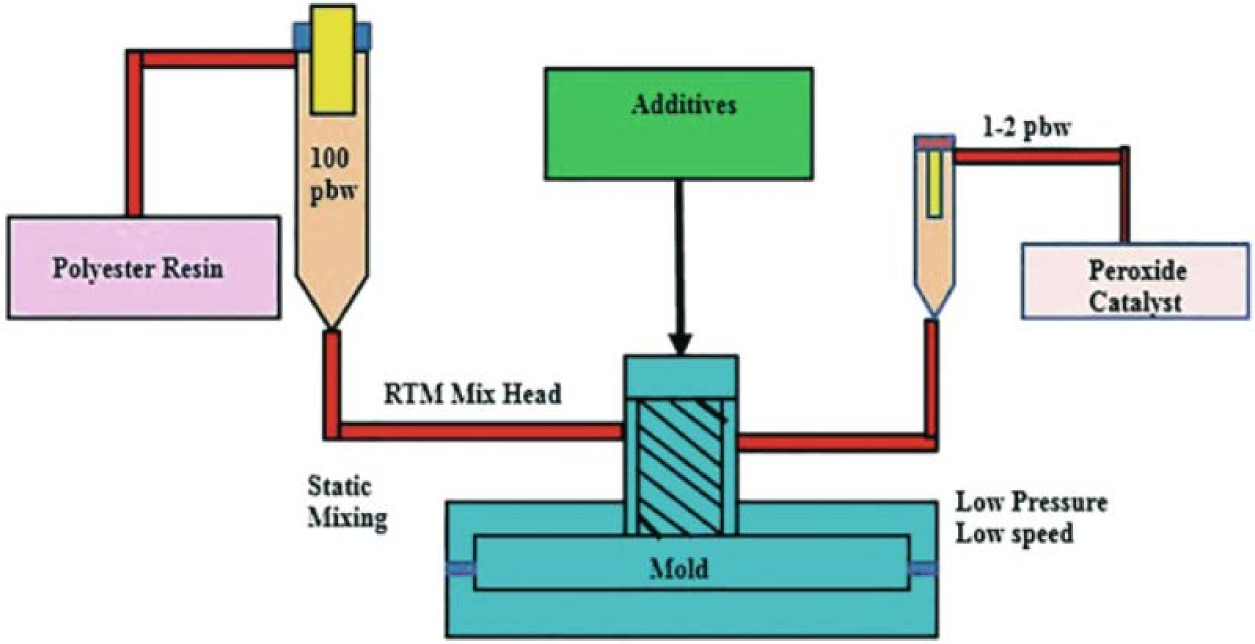
- **Process**:
- A mold is prepared and treated with a release agent.
- Reinforcing fibers (typically glass or carbon mats) are laid manually over the mold.
- Resin (usually epoxy or polyester) is applied with brushes or rollers to impregnate the fiber.
- The composite is left to cure at room temperature or under mild heat.

- **Advantages**:
- Low tooling cost.
- Ideal for large parts with simple geometries (e.g., bumpers, body panels).

- **Limitations**:
- Labour-intensive, poor control over fiber volume, not suitable for mass production.

https://www.researchgate.net/figure/Hand-lay-up-process-for-fabricating-composite-materials_fig1_305218585

2. Resin Transfer Moulding (RTM)



- **Description**: A closed-mold process suitable for medium-to-high volume production.

- **Process**:
- Dry fiber preforms are placed into a matched mold.
- The mold is closed, and resin is injected under pressure.
- The system is cured under heat, forming a strong, consistent composite.

- **Advantages**:
- High surface finish on both sides.
- Good dimensional control, low void content.
- Applicable for structural automotive parts like hoods and doors.

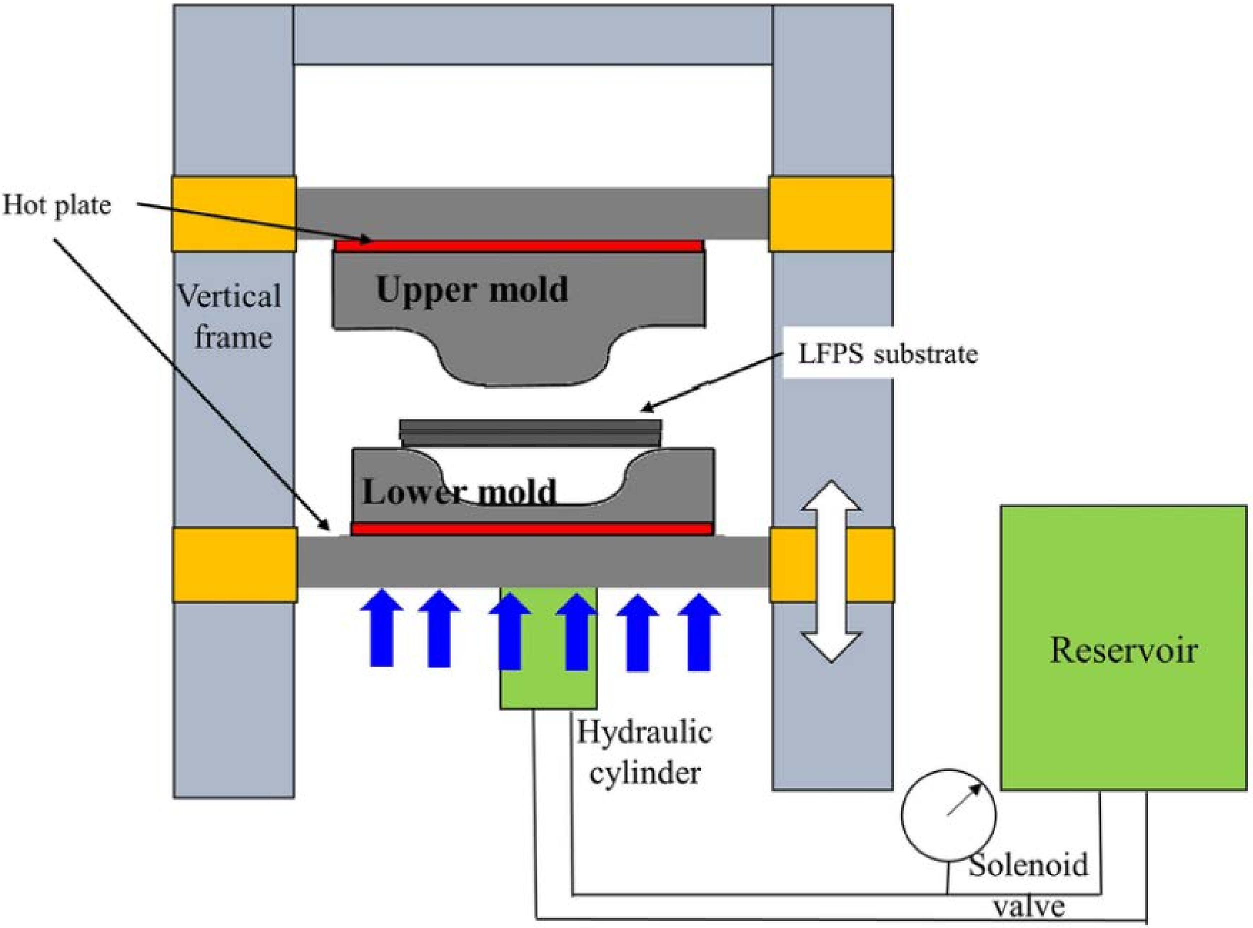
- **Limitations**:
- More expensive molds than hand lay-up.
- Careful control of injection parameters is required.

https://www.sciencedirect.com/topics/physics-and-astronomy/resin-transfer-molding

Journal of Engineering Research 13 **(2025)** 1001–1023

Composites

3. Compression Moulding



- **Description**: Widely used for high-volume manufacturing of composite automotive parts, particularly with SMC (Sheet Moulding Compounds) and BMC (Bulk Moulding Compounds).

- **Process**:
- A pre-measured charge (SMC/BMC) is placed in a heated mold cavity.
- The mold is closed, applying heat and pressure to cure the composite.

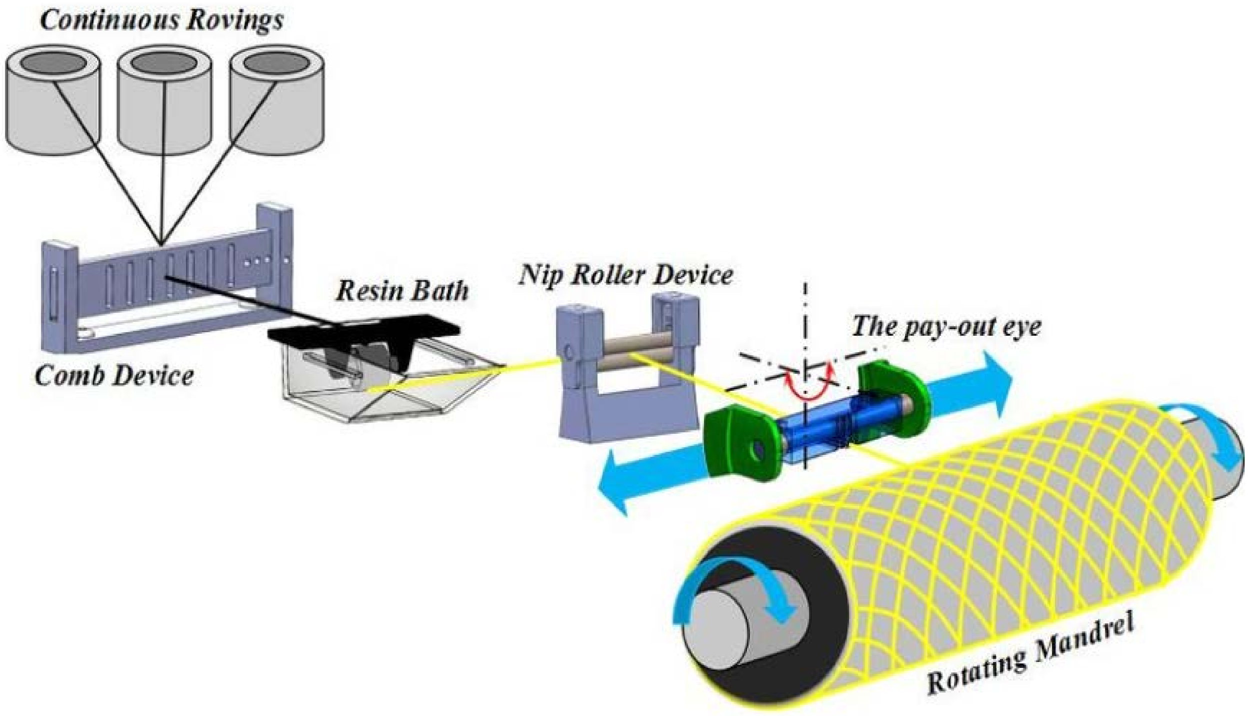
- **Advantages**:
- High production rates and excellent repeatability.
- Suitable for complex shapes like underbody shields, fenders, and structural panels.

- **Limitations**:
- High initial tooling cost.
- Limited to thermosetting matrices.

https://www.researchgate.net/figure/Schematic-diagram-of-compression-molding-machine-using-composite-material_fig1_344094072

Journal of Engineering Research 13 **(2025)** 1001–1023

4. **Filament Winding**



- **Description**: Primarily used to fabricate hollow, cylindrical, or spherical parts (e.g., drive shafts, pressure vessels).

- **Process**:
- Continuous fibers are soaked in resin and wound onto a rotating mandrel in a predetermined pattern (helical or hoop winding).
- The resin is cured and the mandrel removed.

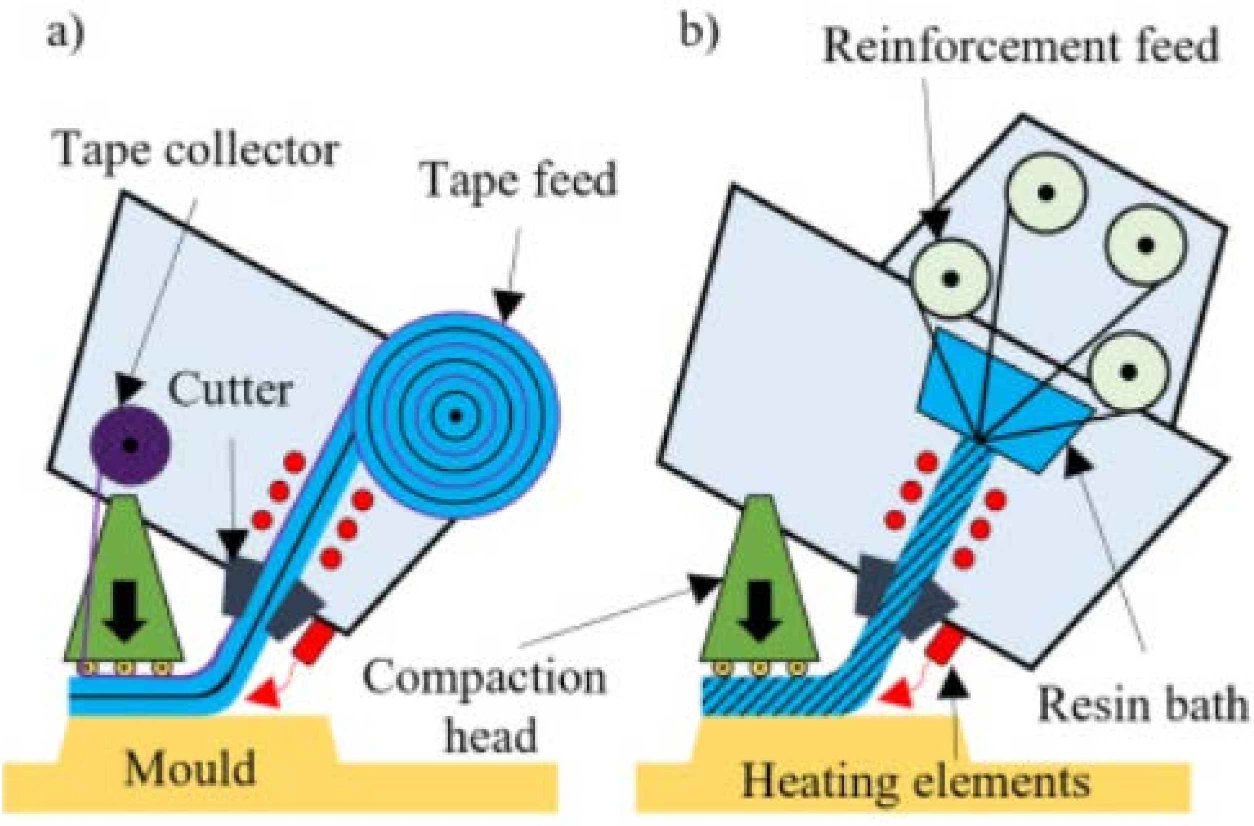
- **Advantages**:
- High strength-to-weight ratio due to aligned fibers.
- Automated and precise.

- **Limitations**:
- Restricted to symmetric geometries.
- Limited design complexity.

Journal of Engineering Research 13 **(2025)** 1001–1023

Composites

5. Automated Fibre Placement (AFP) / Automated Tape Laying (ATL)



a) Automated tape laying and b) automated fibre placement.

- **Description**: Advanced, robotic methods for placing fiber tows or tapes in precise orientations.

- **Process**:
- AFP uses narrow tows, while ATL uses wide prepreg tapes.
- Computer-controlled heads place materials on a mold, optimizing fiber orientation for load paths.

- **Advantages**:
- High structural efficiency.
- Reduced waste and labor.
- Used in high-performance automotive components and aerospace-grade parts.

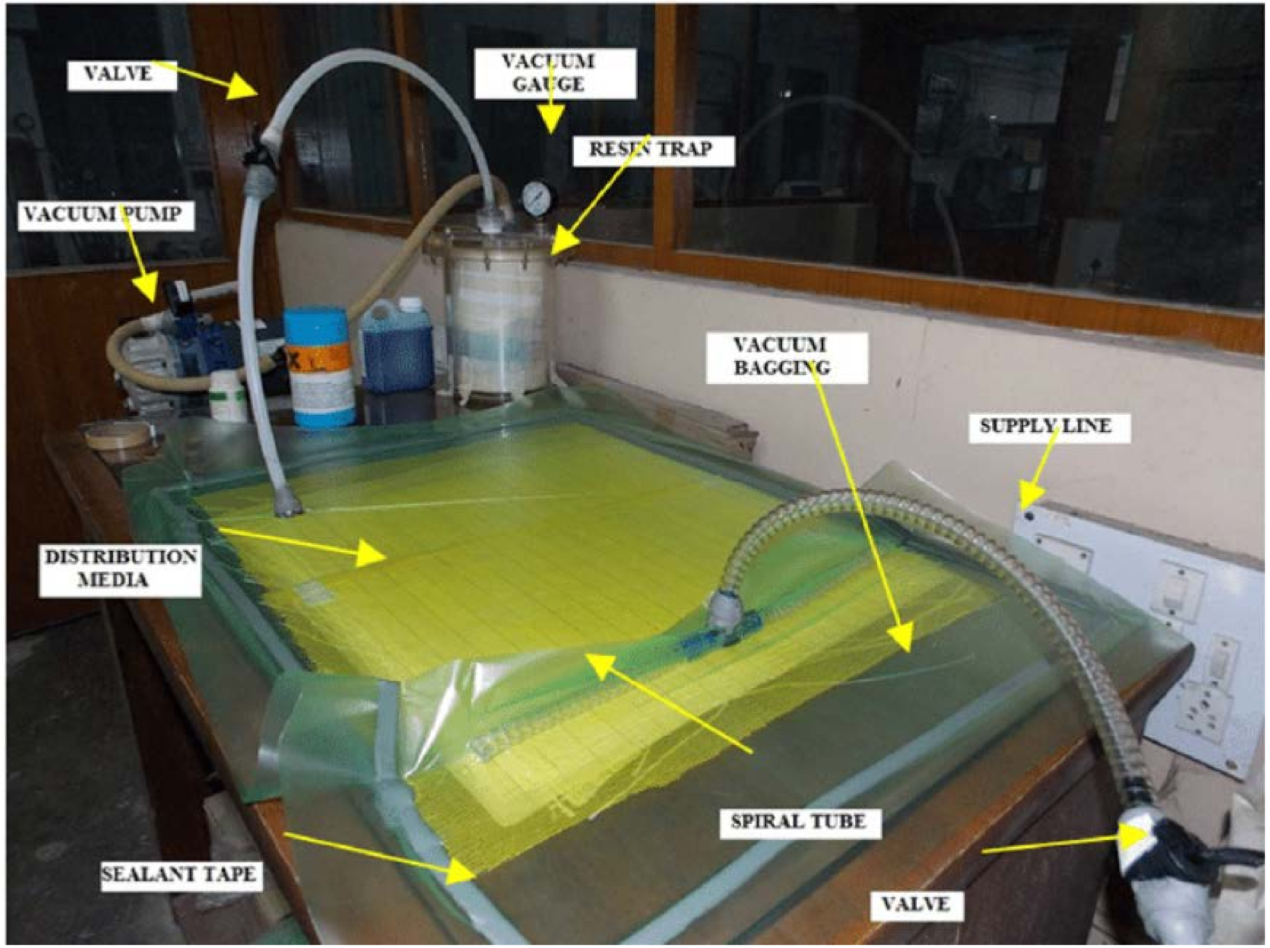
- **Limitations**:
- High capital investment.
- Requires sophisticated design and programming.

Journal of Manufacturing Processes 85 **(2023)** 858–874

Journal of Engineering Research 13 **(2025)** 1001–1023

Composites

6. Vacuum Assisted Resin Transfer Moulding (VARTM)



- **Description**: A cost-effective variant of RTM, where vacuum is used instead of pressure to infuse resin.

- **Process**:
- Dry fiber reinforcement is laid on a mold and covered with a vacuum bag.
- A vacuum draws resin through the fiber network.
- Once infused, the part is cured.

- **Advantages**:
- Lower cost than RTM.
- Good for large parts like roof panels and hoods.
- Lower void content than hand lay-up.

- **Limitations**:
- Slower cycle times.
- Less suitable for complex shapes compared to closed mold RTM.

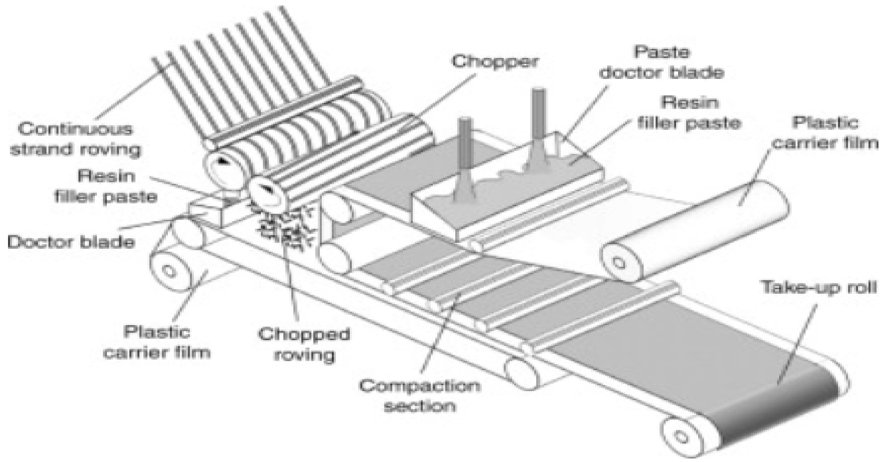
https://www.researchgate.net/figure/Setup-for-vacuum-assisted-resin-transfer-moulding-VARTM_fig1_282858451

Journal of Engineering Research 13 **(2025)** 1001–1023

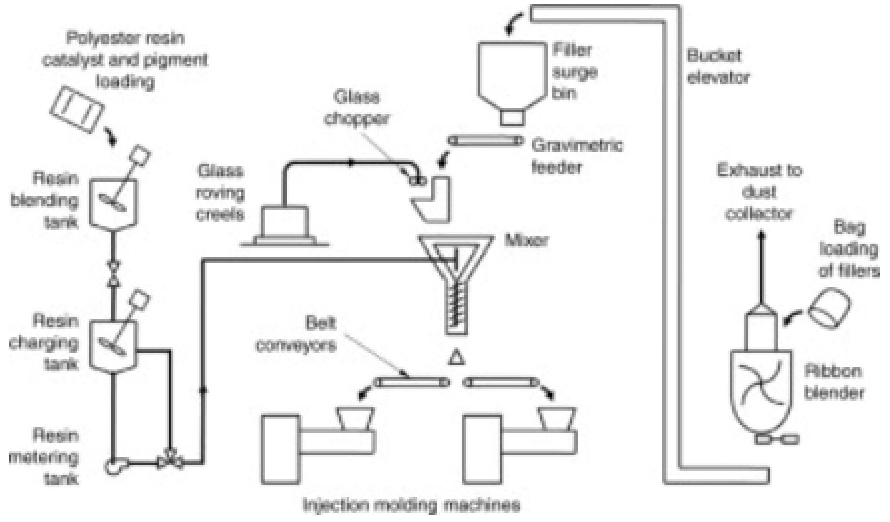
Composites

7. **Sheet Moulding Compound (SMC) and Bulk Moulding Compound (BMC) Techniques**

SMC



BMC



- ❑ **SMC**: Pre-mixed, fiber-resin sheets used for high-strength panels (doors, hoods).
- ❑ **BMC**: Dough-like mixture of resin, fibers, and fillers for compression molding of complex shapes.
- ❑ **Process**:
- ❑ Material is placed in a heated mold and compressed.
- ❑ Rapid curing yields strong, detailed parts.
- ❑ **Advantages**:
- ❑ High throughput, dimensional accuracy.
- ❑ Used in structural and semi-structural car parts.
- ❑ **Limitations**:
- ❑ Limited to thermoset matrices.
- ❑ Surface finish and toughness can vary.