CHAPTER 8

Rapid Prototyping Processes

8.1 Stereolithography (SLA)

Process Description

A low-power laser beam is directed by a mirror to trace a thin 2D cross-section in a liquid photopolymer resin that is stored in a build chamber. Through the process of photopolymerisation, a layer of hardened and cured 3D pixels of polymer are created, a process which only takes place near the surface due to absorption and scattering of the laser beam. The build platform is lowered down an amount equal to the thickness of the previously cured layer, and a sweeper blade moves across replenishing a layer of resin. The laser traces out the next 2D cross-section and the process is repeated. The self-adhesive property of the material used causes the layers to bond and, after many layers have been cured, a 3D part is built up. The completed part is drained, washed in solvent to remove excess resin and subjected to UV light to cure the component completely, after which support constructions are removed by cutting (Figure 8.1).

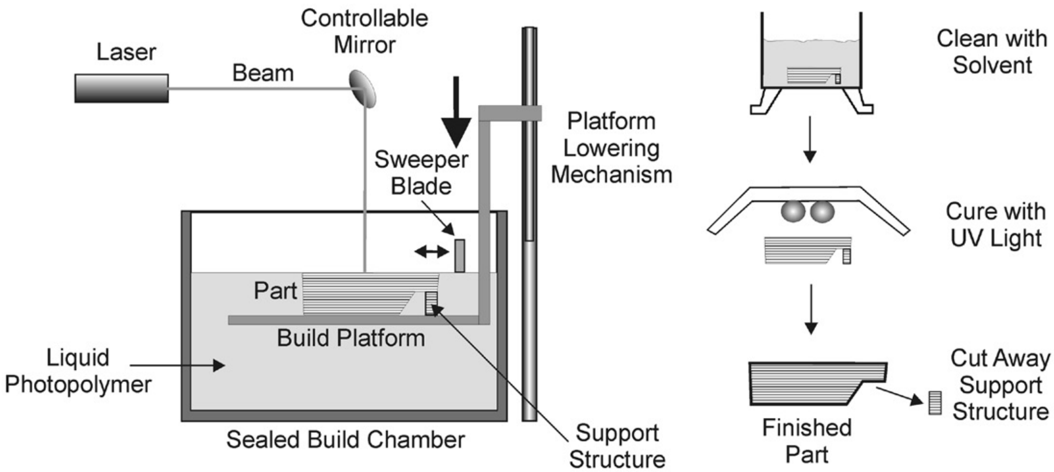

Figure 8.1: Stereolithography.

Manufacturing Process Selection Handbook. http://dx.doi.org/10.1016/B978-0-08-099360-7.00008-2

Materials

- Liquid form of photopolymers such as elastomer, epoxy, urethane, acrylate and vinyl ether.
- Liquid photopolymer can be clear or white.

Process Variations

- Laser types can be UV He:Cd or argon ion, up to 1 W in power.
- Solid Ground Curing (SGC): uses UV light to cure an entire layer of light-sensitive resin, the area being pre-defined by a photomask.
- Solid Object Ultraviolet Laser Plotter (SOUP): the laser is mounted and moved by a controlled mechanism in the horizontal plane above the build chamber of photopolymer, rather than being static and directed by mirrors.

Economic Considerations

- Moderately fast build speed, though large parts can take a day to fully complete.
- Automated process, but skilled labour required.
- Lead times are 1–2 weeks.
- Material utilisation is high. Support structures represent waste.
- Waste material must be disposed of properly. Cannot be recycled.
- Reworking costs are high.
- Photopolymers are expensive and the process requires that the whole build chamber is filled.
- Economical for low production runs 1–20 parts.
- Equipment costs are moderate.
- Direct labour costs are low.
- Some finishing may be required, but final curing also adds time.

Typical Applications

- Non-functional prototypes.
- Form and fit parts in assemblies.
- Product concept models.
- Medical models.
- Casting patterns.
- Snap fits and hinges.

Design Aspects

- Complex and intricate 3D parts created in CAD.
- Undercut features, cantilevered walls and overhangs require support structures to be designed as part of the CAD model or manually on the machine.

- Part should be orientated in the build chamber in order to reduce the amount of support structures.
- Supports can take the form of gussets, ceilings, webs or points.
- Anisotropy in material properties exist due to the additive layer method. Strength weakest in vertical build direction.
- Tensile strengths up to 75 MPa are possible, depending on material used.
- Increased strength can be achieved at certain locations by increasing layer thickness.
- Conventional machining processes can be used for non-standard details, e.g. threads.
- The finished part is translucent.
- Layer thickness = 0.025–0.15 mm.
- Typical maximum dimensions of part = 600 mm × 500 mm × 500 mm.
- Minimum section = 0.1 mm.

Quality Issues

- Calibration of the laser is required periodically for some systems.
- Green creep distortion tests can help assess the dimensional stability of the laser-cured resins.
- Laser exposure and scan speeds need to balance full curing and process speed.
- Total thickness layer is related to the scanning speed and depth penetration factor of the photopolymer resin.
- A short delay called a 'dip delay' is required after laser curing of a layer, so that liquid photopolymer can settle flat and evenly, inhibiting bubble formation.
- The liquid photopolymer is difficult to work, toxic and pungent, and requires safe handling procedures.
- The selection of the correct photopolymer is associated with strength, shrinkage and distortion of the part that is tolerable post-curing.
- Material properties may change over time, accelerated by light, moisture, heat and chemical environments.
- The machine is sealed to prevent toxic fumes from escaping, generated by the laser solidifying the resin.
- Avoid the location of support structures on planes where good surface finish is required.
- Support structures must be removed from part manually, but the process is simple and quick.
- Additional post-processing may be required for part finishing.
- The durability of the part is limited when exposed to sunlight.
- Finished part can be painted.
- Tolerances achievable = ±0.1 to ±0.2 mm.
- Typical surface roughness = 2 μm Ra.
- Surface finish is excellent in comparison to other rapid prototyping technologies.

8.2 3D Printing (3DP)

Process Description

A printing head (similar to those found in inkjet printers) deposits a liquid binder on to a powder in a build chamber. The powder particles become bonded together and the build platform is lowered down an amount equal to the thickness of the layer created. The powder is replenished in the build chamber from a similar powder supply chamber adjacent to it, compacted and levelled on top of the last bonded layer using a roller. The process is repeated, building up a 3D part. The completed part is cleaned of excess powder and typically impregnated with a sealant (Figure 8.2).

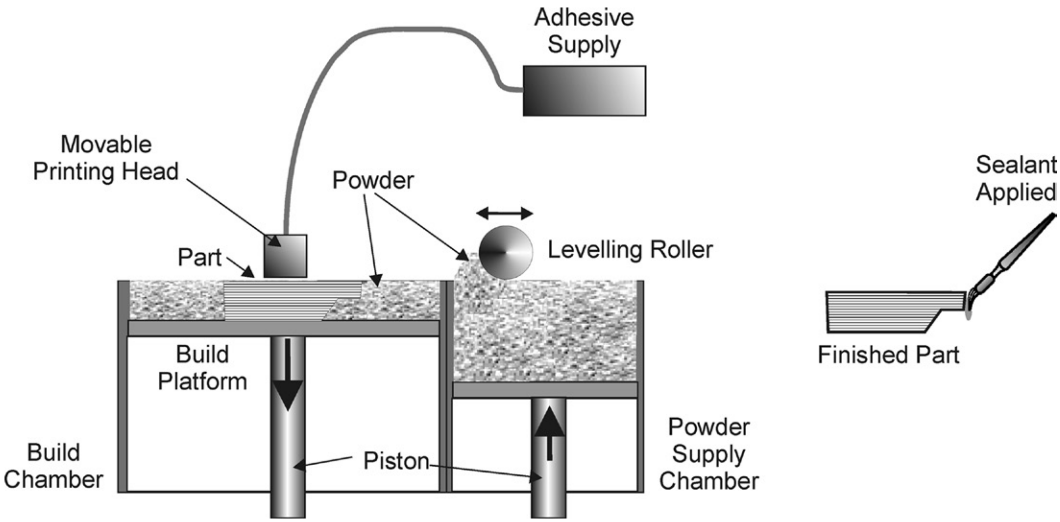

Figure 8.2: 3D Printing.

Materials

- Powder form of stainless steel, bronze, ceramics, moulding sand, plaster and starch.
- Liquid form of binder such as wax, epoxy resin, elastomer and polyurethane.

Process Variations

- Single-head (takes several passes) or multi-head (just one pass) printing devices used.
- A sintering stage can be added to the process to further bond the powders.
- Jetted Photopolymer System (JPS): wide array of printing heads are used to deposit a photopolymer resin, as used in Stereolithography (see PRIMA 8.1), which is cured through exposure to UV light.
- Thermal Phase Change Inkjet Printing: uses two separate printing heads, one dispensing a thermoplastic melt and the other hot wax support material, to create a 2D layer that hardens on contact. A milling tool machines the surface level and the wax is dissolved or melted out.

Economic Considerations

- Fast build speed.
- Automated and very flexible process, but skilled labour required.
- Lead times are typically less than 1 week.
- Materials are low cost.
- Material utilisation is high.
- Excess powder material is reusable.
- Equipment costs are low.
- Direct labour costs are low.
- Finishing processes are generally required, which adds cost.

Typical Applications

- Product concept models.
- Models for ergonomic testing.
- Surgical planning models.
- Coloured models, e.g. stress patterns from Finite Element Analysis (FEA).
- Architectural models.
- Non-functional prototypes.
- Consumer goods.
- Packaging.
- Models for casting and moulding.
- Patterns and cores for casting processes.

Design Aspects

- Complex and intricate 3D parts created in CAD.
- Any powder material not bonded and unused in the build chamber acts as a support medium for any overhanging or undercut features on the part. No additional support structures are therefore needed.
- Parts should be orientated in the build chamber with the height being the smallest dimension in order to reduce the number of layers created.
- Anisotropy in material properties exist due to additive layer method. Strength weakest in vertical build direction.
- Tensile strength depends on the material being used, e.g. plaster powder models have <5 MPa tensile strength.
- Binder and powder each contribute approximately 50% of material by volume to a component.
- Layer thickness = 0.05–0.15 mm.
- Typical maximum dimensions of part = 600 mm × 500 mm × 400 mm.
- Minimum section = 0.2 mm.

Quality Issues

- Parts are fragile direct from the process.
- Epoxy resin and cyanoacrylate adhesive can be used to impregnate the finished part to improve finish, durability and part strength. Wax also used but not as strong as resins or adhesives.
- Can introduce multiple colours to the model.
- Accuracy is dependent on binder droplet size, powder size, the diffusion of the binder into the powder, and printer head positional resolution.
- 'Stair-stepping' features on sloping surfaces in the vertical build plane can be created.
- Not particularly suitable where an accurate fit is required for the part due to relatively poor tolerances and strength.
- Tolerances achievable = ±0.1 to ±0.5 mm.
- Typical surface roughness = 60 μm Ra.
- Finish is grainy and typically requires additional finishing processes.

8.3 Selective Laser Sintering (SLS)

Process Description

A high-power laser beam directed by a mirror is used to sinter powdered material in thin 2D cross-sections. The powder is in a sealed chamber with a nitrogen atmosphere to prevent oxidation. It is pre-heated using infrared heaters to a temperature just below the melting temperature of the powdered material. The build platform is lowered down an amount equal to the thickness of the sintered layer. A roller replenishes the layer of powder from adjacent powder supply chambers, the laser traces out the next 2D cross-section, and the process is repeated until a 3D structure is built up. Excess powder not sintered on each layer acts as a support for the part being built. The part is removed and excess powder is removed by brushing or vacuuming (Figure 8.3).

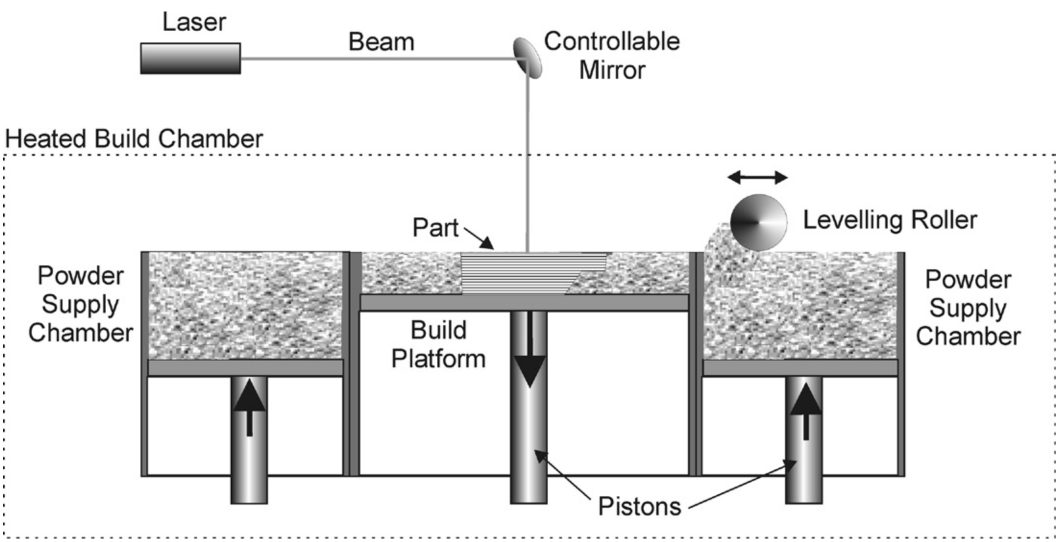

Figure 8.3: Selective Laser Sintering (SLS).

Materials

- Powder form of heat-fusible thermoplastics (including glass filled), elastomers and wax.
- Powdered metals with binder, e.g. stainless steel, tools and alloy steels, titanium, tungsten, copper alloy, aluminium and nickel super alloys.
- Powdered ceramics and moulding sand (with binder).

Process Variations

- Direct Metal Laser Sintering (DMLS): used for processing metal and ceramic composite parts using very fine powders with no binders, and high-powered lasers to sinter the particles directly in an inert atmosphere. Achieves very high part densities, but support structures are required for overhanging features. Typically parts will go through a number of post-processing stages, including support removal, shot peening (see PRIMA 9.6) and polishing, to improve fatigue resistance and finish.
- Laser types: Yb-fibre or CO_2, up to 100 W in power. Up to 200 W for DMLS.

Economic Considerations

- Medium build speed.
- Automated process, but skilled labour required.
- Lead times are typically 1 week.
- Material utilisation is high.
- Leftover powder material is directly reusable.
- Powdered material cost is low to moderate, depending on type.
- Economical for production runs of 1–50+, depending on size and complexity. DMLS can be viable for larger volumes, 1,000+.
- Equipment costs are high.
- High energy requirement.
- Direct labour costs are low.
- Some finishing may be required.

Typical Applications

- Final functional components in low to moderate volumes, e.g. impellers, fuel nozzles for aerospace sector.
- Functional prototypes, e.g. for experimental testing, wind tunnels, etc.
- Form and fit parts in assemblies.
- Product concept models.
- Patterns, moulds and cores for casting and moulding.
- Rapid tooling.
- Medical and dental implants.
- Models for ergonomic testing.
- Snap fits and hinges.

Design Aspects

- Complex and intricate 3D parts created with CAD.
- Any powder material not sintered in the build chamber acts as a support medium for any overhanging or undercut features on the part. No additional support structures are therefore needed.

- Parts should be orientated in the build chamber with the height being the smallest dimension in order to reduce the number of layers created.
- Anisotropy in material properties exist due to additive layer method. Strength weakest in vertical build direction.
- Approximately 50 MPa tensile strength for some thermoplastics, 300 MPa for bronze-impregnated steel, 1 GPa+ for titanium using DMLS.
- Parts can be machined using conventional processes.
- Layer thickness = 0.075–0.15 mm, depending on material used.
- Thinner layers can be achieved with DMLS >0.02 mm.
- Typical maximum dimensions of part = 450 mm × 375 mm × 325 mm.
- Minimum section = 0.4 mm.

Quality Issues

- Control of build chamber temperature just below the material's melting point is important to facilitate fusion between layers as the heat from the laser only needs to raise the temperature a small amount for sintering. Also important in order to minimise thermal distortions.
- Large parts can take many hours to cool before handling is possible.
- Machine needs thorough cleaning when changing material powder types to avoid contamination.
- Stress relieving and annealing may be required for metal parts to reduce internal residual stresses.
- Additional curing may be required when using ceramic materials.
- The nitrogen atmosphere maintained in the build chamber also prevents possibility of explosion of the powder.
- 'Stair-stepping' features on sloping surfaces in the vertical build plane can be created.
- Greater than 99% densities can be achieved after sintering; 100% density is achievable when impregnated with another material.
- Impregnation improves mechanical properties and surface finish. Typically a lower melting temperature metal alloy such as an alloy of copper is used for impregnation.
- Finished part can be painted and surface coated.
- Tolerances achievable = ±0.05 to ±0.25 mm.
- Typical surface roughness = 7–10 μm Ra.
- Finish is related to coarse powders used, and may require additional finishing processes. Powder diameter is usually between 20 and 100 μm.

8.4 Laminated Object Manufacturing (LOM)

Process Description

Sheet material coated with an adhesive is moved into the build area using a feed roll and pressure is applied using a heated roller to bond to the layer below. The sheet is cut using a CO_2 laser beam directed by a mirror and optic heads to create the required 2D profile. The build platform is lowered down an amount equal to the thickness of the layer created and the process is repeated, building up a 3D part. Excess sheet surrounding the 2D profile is cross-hatched with the laser for easier removal (chopped away in sections later) and the remaining sheet is moved away on a waste take-up roll. The finished part is removed and is typically sanded down to improve the surface finish and then sealed (Figure 8.4).

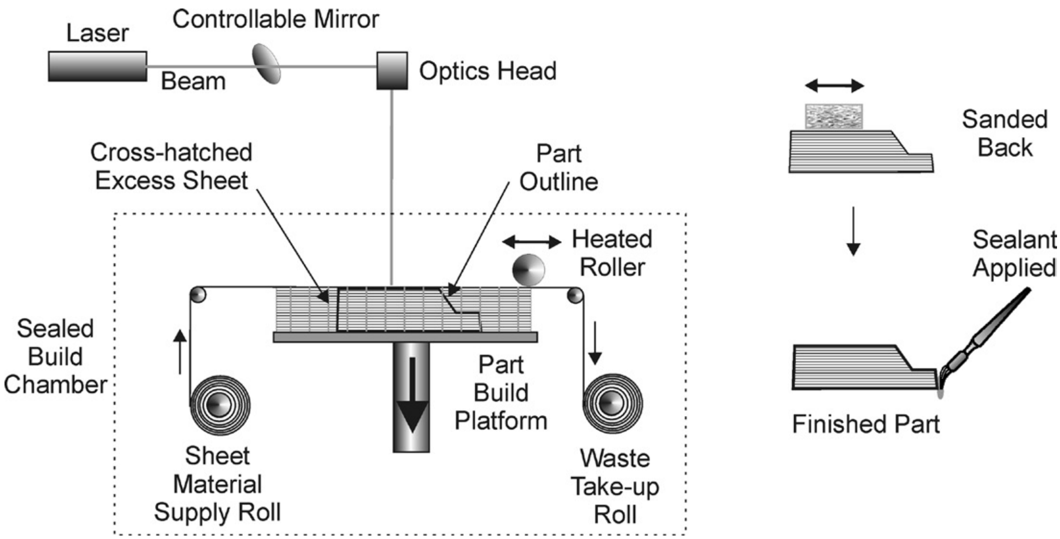

Figure 8.4: Laminated Object Manufacturing (LOM).

Materials

Thin sheet form of paper, some thermoplastics, metal foils and ceramics.

Process Variations

- Several commercial variants use a knife instead of a laser to cut the sheets.
- Solvents rather than adhesives can be used to bond sheets of thermoplastics.
- CO_2 laser power varies between 25 and 50 W depending on material being cut.

Economic Considerations

- Medium speeds, but varies widely depending on material and complexity.
- Lead times are less than 1 week.
- Material costs are very low.
- Material utilisation is low to moderate.
- Waste material is not reusable, although possible to recycle.
- Economical for one-offs.
- Equipment costs generally moderate.
- Direct labour costs are moderate. Skilled labour required at all times.
- Finishing time and costs can be moderate to high.

Typical Applications

- Large product concept models.
- Non-functional prototypes.
- Casting patterns and cores.
- Tooling models.

Design Aspects

- Complex and large 3D parts created with CAD.
- Cannot create hollow parts.
- No additional support structures are required.
- Undercuts and re-entrant features are very difficult to create without manual intervention.
- Parts should be orientated in the build chamber with the height being the smallest dimension, in order to reduce the number of layers created.
- Tensile strength of finished part is highly anisotropic, e.g. for paper <5 MPa tensile strength at right angles to the lay-up direction, >60 MPa in line with the lay-up direction.
- Not suitable for conventional machining processes due to possibility of delamination.
- Layer thicknesses range = 0.05–0.2 mm.
- Typical maximum dimensions of part = 800 mm × 550 mm × 500 mm.
- Minimum section = 0.2 mm.

Quality Issues

- Little shrinkage and distortion during processing.
- Can be complex and time consuming to create certain geometries.
- Not suitable for parts subjected to any shear forces in the axis of the build plane due to relatively weak bonded nature of sheets.
- ‘Stair-stepping’ features on sloping surfaces in the vertical build plane can be created.
- Laser is carefully modulated to penetrate to a depth of exactly one layer thickness.

- Combustible materials such as paper represent a fire hazard.
- Build chamber must be sealed to, as the process produces smoke that needs extraction and fire extinguishing equipment located in the build chamber.
- Post-processing is needed to protect the component from ingress of moisture through the sheet layers, which can cause swelling.
- Variety of sealants used on finished part: wax, paint, varnish, urethane, silicon or epoxy resin depending on protection needed.
- Finished part can also be painted to improve appearance and to add colour.
- Tolerances achievable = ±0.1 to ±0.25 mm.
- Typical surface roughness = 30–40 μm Ra.
- Surface finish is poor in comparison to other rapid prototyping processes, and requires additional finishing processes.

8.5 Fused Deposition Modelling (FDM)

Process Description

Solid material, usually in filament form, is melted and extruded through a heated nozzle to create a molten bead of build material. The build chamber is maintained at a temperature just below the melting point of the build material. The controllable nozzle is moved in the horizontal plane, depositing the molten bead to create a thin layer of the required 2D profile. The molten bead solidifies and effectively cold welds on contact with the previous layer. The build platform is lowered down an amount equal to the thickness of the solidified layer, and the process is repeated, building up a 3D part. Additional support material for overhangs and undercuts is simultaneously deposited during the build process using a second nozzle. The support material can be dissolved away after the part is removed from the build chamber (Figure 8.5).

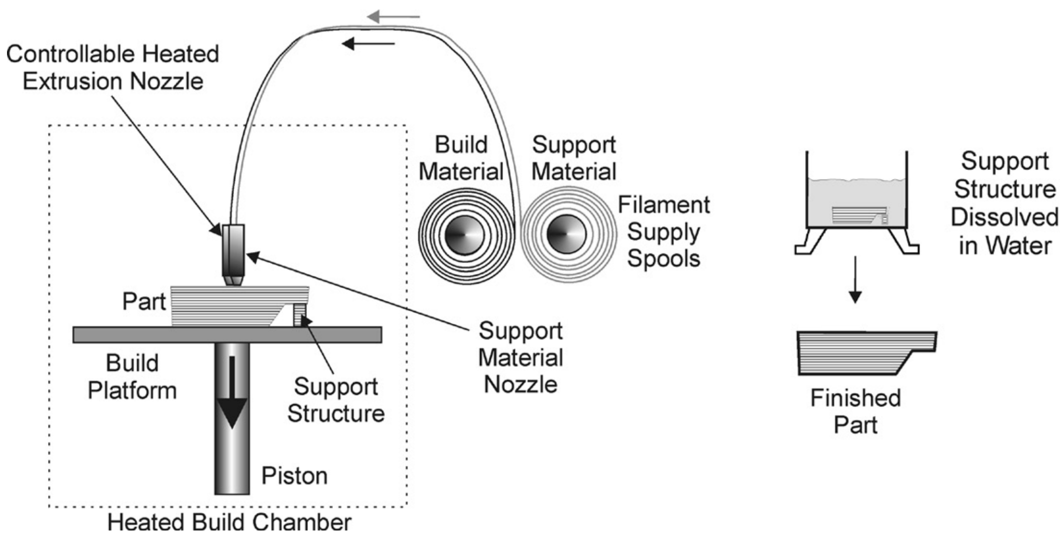

Figure 8.5: Fused Deposition Modelling (FDM).

Materials

- Build material supplied in filament coils (diameter 1.5 mm).
- Commonly, wax, elastomers and a number of thermoplastics are used as the build material.
- Ceramics (with binder material), eutectic metals and glass-fibre-reinforced materials have been used to produce components on a limited basis.
- Support materials include wax and nylon-like material.

Process Variations

- Some process variants use pellet form of the build material rather than filament.
- Support materials are either water-soluble or broken away.

Economic Considerations

- Build speeds are slow (to medium), but dependent on cross-section size.
- Lead times are 1–2 weeks.
- Material utilisation is high.
- Both support and build material are moderately expensive.
- Economical for low production runs of small components and one-offs.
- Equipment costs generally low to moderate.
- Direct labour costs are low.
- Finishing costs are low to moderate.
- Support material removal and surface finishing are typical post-processing operations.

Typical Applications

- Functional prototypes, e.g. for experimental testing, wind tunnels, etc.
- Product concept models.
- Patterns and cores for casting processes.
- Rapid tooling.
- Medical models.

Design Aspects

- Complex and intricate 3D parts created with CAD.
- Support structures must be designed and fabricated for undercuts and overhanging features.
- Supports can take the form of boxes, ceilings or webs.
- Part should be orientated in the build chamber in order to reduce the amount of support structures.
- More suited to small-volume, medium section components.
- Difficult to build thin wall sections, acute angles or sharp edges in vertical plane due to contact pressure with extruded bead from nozzle, which could cause deformation.
- Can produce internal structures in the part to save weight/volume, e.g. a lattice structure. Soluble support material is required.
- Conventional machining processes can be used for non-standard details, e.g. threads.
- Anisotropy in material properties exist due additive layer method. Strength weakest in vertical build direction.
- Typical tensile strength is approximately two-thirds of the strength of the same thermoplastic that has been injection-moulded.

- Tensile strength for thermoplastics: ABS = 35 MPa, PC = 60 MPa.
- Layer thickness = 0.05–0.75 mm.
- Typical maximum dimensions of part = 600 mm × 600 mm × 500 mm.
- Minimum section = 0.3 mm.

Quality Issues

- Control of build chamber temperature is important to minimise energy needed to melt the filament at the extrusion nozzle.
- Layer thickness and build accuracy is related to the nozzle diameter.
- Nozzle speed and material extrusion rate require control to provide consistent deposition rate and layer thickness.
- 'Stair-stepping' features on sloping surfaces in the vertical build plane can be created.
- Components exhibit virtually no porosity.
- Process can be installed anywhere being non-toxic and environmentally safe.
- Different colour build material can be supplied.
- Uses materials with high structural stability, temperature, chemical and water resistance properties.
- Tolerances achievable = ±0.1 to ±0.25 mm.
- Typical surface roughness = 6–12 μm Ra.
- Some finishing may be required to improve surface finish, depending on application.