

Tutorial

The rapid prototyping technologies

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Keywords

Rapid prototypes, Assembly, Sintering, Modelling

Abstract

This paper reviews the various technologies available for rapid prototyping including stereolithography, selective laser sintering, laminated object manufacturing, fused deposition modelling, multi-jet modelling, three-dimensional printing. It also covers surface roughness considerations and mechanical properties including dimensional accuracy and compares costs of various systems and general trends in equipment performance.

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1. Introduction

The American automotive industry is credited as being the primary driver behind the early push to develop processes that could produce physical components quickly and without the need for tooling. Such demands had previously been difficult to achieve primarily through the lack of computational capabilities however in the early 1980s, a step change occurred with the emergence of three-dimensional computer aided design (CAD) systems. The goal of shorter product lead times and more individually styled products is within the sight as the concept of “free form fabrication” (FFF) or “rapid prototyping” (RP) begins to take shape.

Commercial RP systems began to appear in the USA in the late 1980s and some 20 years later America remains the dominant player in this global market. Alternate systems have been developed worldwide, notably in Japan, Germany, Russia, China and more later in Israel. However, due to the patent position, it is the American equipment suppliers who initially developed the market and subsequently maintained their dominant position.

Current successful RP equipment suppliers have developed partnerships and local agency agreements on a worldwide basis and almost without exception they are all represented in one form or another in the UK.

2. What is RP?

RP is a generic term for a number of technologies that enable components to be made without the need for conventional tooling in the first instance or indeed without the need to engage the services of skilled model-makers.

Many manufacturing processes are subtractive, in that they modify the geometry of a mass of material by removing parts of the material until the final shape is achieved. Conventional milling and turning are good examples of subtractive processes.

By contrast, RP techniques are additive processes. RP components are built-up gradually in layers until the final geometry is obtained. The way in which the layers are produced, however, and the materials in which parts can be built vary significantly between the different RP processes.

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The starting point for the RP process is typically a 3D CAD model prepared and exported to meet the requirements of a given technology. Various other “inputs”, in addition to CAD, can be used to create RP components; these include medical applications such as MRI and CAT scanning as well as point cloud data generated by engineering scanning or digitising systems. Whatever be the source of the original data it is reformatted into an stl file and sliced horizontally, each individual slice is subsequently presented to the selected RP manufacturing process. The RP system will subsequently reproduce the sliced data thereby creating a physical example of the original “CAD” data (Figure 1).

Each RP technique has its own advantages and disadvantages. These must be understood thoroughly before an RP process is selected; otherwise, a part that does not completely fulfil the requirements of the end-user may be produced, and disappointment in the use of RP technology is likely to occur.

3. What can RP be used for?

To many organisations new to RP, it is not always clear for what purposes the technology can be used. The major uses documented to date include the following.

3.1 Concept models

RP techniques allow prototypes of many complex parts to be made more quickly and cheaply than when using conventional manufacturing processes. Design teams can therefore check the prototype at an early stage and make any necessary modifications to the design before any commitment to production tooling is made. An RP part can be used as a communication tool not only within the core design team, but also with other interested

parties. For example, RP parts can be given to sales teams so that an early response to a proposed design can be obtained from potential customers. In addition, the same component can be given to the production team to enable them to plan how best to manufacture the part if it is sanctioned for production following customer approval.

3.2 Functional or semi-functional components

Some RP processes allow fully functional parts to be built directly, if the intended application for the part is not too demanding. RP parts can also be used in assemblies and may perform the function of a final production part satisfactorily. More often, however, semi-functional parts are made using RP processes, as the RP materials often do not have adequate physical properties for the final application. These semi-functional parts can still be used to check that parts can be easily assembled together or to perform experimental tests that rely only on the part geometry and not on the material properties.

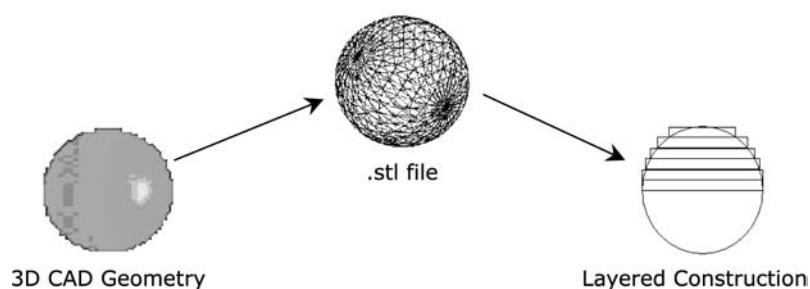
3.3 Master patterns

RP parts can be used as masters to make production tooling. For example, they can be used to produce silicon rubber moulds for the low volume production of functional parts using the vacuum moulding or reaction injection moulding processes. RP parts can also be used as one-off patterns for investment casting moulds, though the RP parts are destroyed during this process. Additionally, RP parts can be used as masters in sand casting foundries.

3.4 Direct tooling

For some applications, RP processes allow production tooling to be made directly. “Soft” tooling that can only be used for low production volumes can be made; soft

Figure 1 The three stages of an RP system



injection mould tools can be made from polymers, for example, that allow up to several hundred shots to be produced. “Hard” or volume production tooling can also be made using relatively new RP processes. For example, injection mould tooling can be made directly in a metal composite that allows over one million shots.

4. Details of RP technologies

The RP industry is relatively young and it is therefore to be expected that some current RP processes will disappear and that others will emerge to become key players in the market in the future.

At present, the prototyping technologies are based on the following five main manufacturing processes.

- *Curing process* – where a photo-sensitive polymer is exposed to a light source in order to harden the polymer.
- *Sheet process* – where thin sheets of a material are cut to shape and stacked on top of each other.
- *Dispensing process* – where a material is melted and then deposited either as a hot filament or as individual hot droplets.
- *Sintering process* – where a powdered material is sintered together using a heat source, typically a laser beam.
- *Binding process* – where a liquid binder is deposited onto a powdered material to bind the powder together.

4.1 RP systems

The market for RP systems remains at the formative stage and due to the dynamic nature of the process itself, it has encouraged many individuals and businesses to develop RP systems.

A survey in 1999 identified some 40 different RP manufacturing approaches. Some of these are well established “main stream” RP systems while others are more recent arrivals with much to prove. Also included in the list are systems that are still at the development stage and may not become commercially available, viable RP systems.

RP systems listed in 1999

3DP	three-dimensional printing
3DWM	three-dimensional welding and milling

BPM	ballistical particle manufacture
CAM-LEM	computer aided manufacturing – laminated engineering materials
CC	contour crafting
CLOM	curved laminated object manufacturing
DLF	direct light fabrication
DLMS	direct laser metal sintering
ECLD-SFF	electrochemical liquid deposition for solid freeform fabrication
EDSSM	extrusion and deposition of semi-solid metals
EFF	extrusion freeforming
EPDFF	electrophotographic powder deposition for freeform fabrication
FDC	fused deposition of ceramics
FDM	fused deposition modelling
FDMet	fused deposition of metals
FFF	fast freeform fabrication
FI	fast inkjet
GMAW	gas metal arc welding
LCRHLS	local chemical reaction heat by laser scanning
LCVD	laser chemical vapour deposition
LDM	laser diode manufacturing
LENS	laser engineered net shape
LM	layered manufacture
LML	laser microchemical lathe
LOM	laminated object manufacturing
M2SLS	multimaterial selective laser sintering
Meso SDM	mesoscopic shape deposition manufacturing
Mold SDM	mold shape deposition manufacturing
PLD	pulsed laser deposition
PPD	pointwise powder deposition
RFP	rapid freeze prototyping
RBC	robocasting
RPBPS	rapid pattern based powder sintering
RSLA	refrigerative stereolithography
SALD	selective area laser deposition
SADVI	selective area laser deposition and vapour infiltration
SGC	solid ground curing
SLA	stereolithography
SLPR	selective laser powder remelting

SLS	selective laser sintering
TIF	temperature induced forming
TLP	thick layer prototyping
WFDM	wirefeed direct metals

The following provide a summary of some of the most popular RP processes in use at present.

4.2 Stereolithography

Stereolithography (SLA) is one of the oldest RP technologies dating back to the mid 1980s. SLA can be used to make parts with complex geometry and with a surface finish comparable to many conventionally machined components. SLA parts are often used as masters to produce silicon moulds for vacuum or reaction injection moulding. When built with a honeycomb cross-section (known as the “QuickCast” build style) they are also often used as sacrificial masters in the investment casting process (Table I).

4.2.1 Method

A vat of polymer contains a platform on which the part is built. The platform can rise and fall within the vat. The platform moves until it is just below (0.050–0.250 mm) the surface of the liquid polymer. A laser traces out the cross-section of one slice of the part (Figure 2). Where the laser hits the polymer it solidifies. The platform then moves down the distance of one slice (0.050–0.250 mm) of the part, and the laser draws the next slice on a fresh layer of liquid polymer. This slice of the part solidifies on top of the previous set slice. When all the slices have been traced by the laser, the platform is removed from the vat and excess liquid polymer is cleaned off the completed part. The completed part is then finally cured in an ultraviolet oven.

4.2.2 Advantages

- Good surface finish;
- Complex geometry, easily obtained; and

Table I Summary of the SLA process

Materials available	Epoxy-based photocurable resins
Minimum laser beam \varnothing	0.200 mm
Layer thickness	0.050–0.250 mm
Finishing available	Models can be lightly sanded and sprayed with standard non-water based paints
Tooling methods available	Vacuum casting, reaction injection moulding, direct injection mould tooling, metal spray tooling, investment casting

- Generally, there is a good accuracy of the geometry.

4.2.3 Disadvantages

- Models need support structures that must be removed as a finishing operation;
- Parts can warp, especially with acrylate resins; and
- Resins are hazardous and need careful handling.

4.2.4 Main suppliers

3D Systems Inc. and EOS GmbH.

4.3 Selective laser sintering

Selective laser sintering (SLS) allows rapid prototypes to be built in a variety of materials so that semi-functional parts can be obtained directly. Parts of complex geometry can be made from the powdered materials used. The fact that powder is used as the base material limits the quality of the surface finish of the final part. Production tooling can be made directly by using SLS parts made of metal powder in the RapidTool process (Table II).

4.3.1 Method

A layer of powdered material is deposited on a platform. A laser beam traces out the cross-section of one slice of the part. Where the laser beam hits the powder, the affected particles fuse together (or *sinter*) (Figure 3). Another layer of powder is then deposited on top of the previous layer using a roller mechanism, and another slice of the part is sintered onto the sintered material in the previous slice. The unsintered material in each layer can act as a support structure for the part itself. When the part is complete, the unsintered material can simply be brushed off.

4.3.2 Advantages

- No post-curing of the parts is needed, unless they are ceramic;
- Parts can often be built without additional support structures; and
- Parts in a range of materials can be obtained directly.

4.3.3 Disadvantages

- Surfaces of the parts are porous, and surface finish can be poor;
- Process machines can take a long time to heat up and cool down;

Figure 2 Schematic view of the SLA process

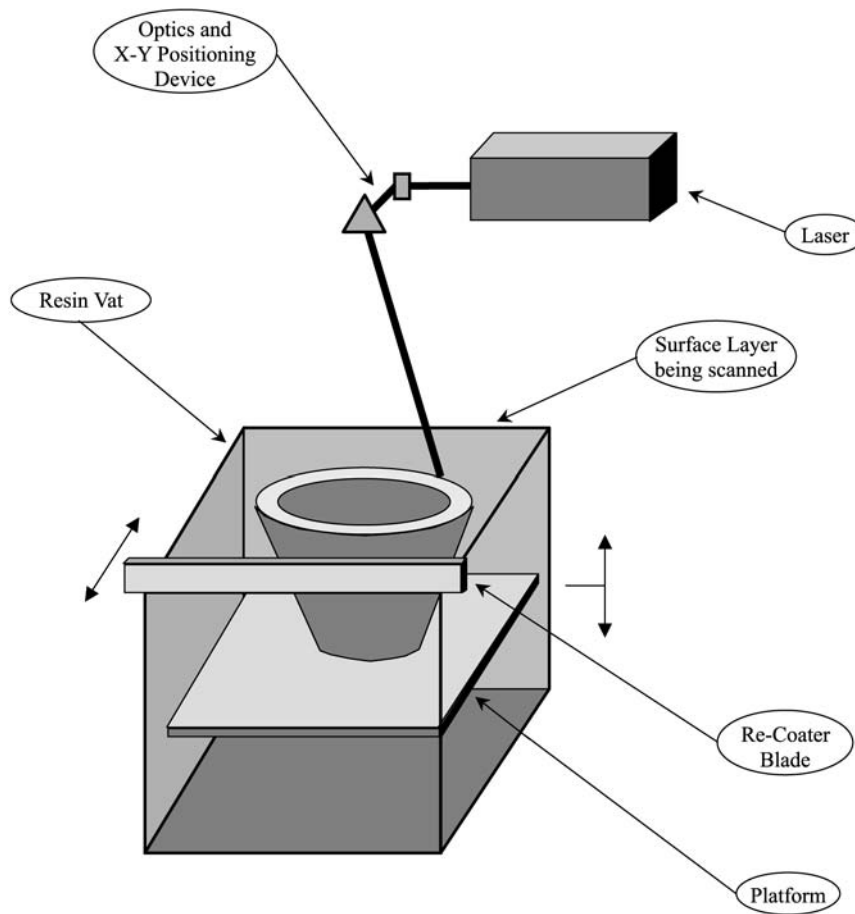


Table II Summary of the SLS process

Materials available	Carbon steel with polymer binder, nylon, polystyrene, polycarbonate, investment casting wax, ceramics coated with binder, zirconium sand coated with polymer, flexible elastomer
Layer thickness	0.080-0.500 mm
Finishing available	–
Tooling methods available	Investment casting, vacuum casting, direct injection mould tooling

- Investment casting requires the surface of master parts to be sealed; and
- Parts can warp significantly.

4.3.4 Main suppliers

DTM Corporation, EOS GmbH.

4.4 Laminated object manufacturing

Laminated object manufacturing (LOM) is often described as turning paper back into wood (though non-paper material is also available for the technique), as LOM is often used to make wooden patterns for sand

casting. These patterns are fairly durable, and therefore re-useable. LOM is one of the cheapest RP technologies and is excellent for making large parts with moderate geometrical complexity (Table III).

4.4.1 Method

A layer of material with an adhesive coating on one side is placed on a platform, adhesive side down. A heated roller passes over the material and sticks the material to the platform. A laser beam then traces the outline of one slice of the part, cutting through the layer of the material (Figure 4). The laser beam then crosshatches the material that does not form part of the cross-section, again cutting through the layer. The platform is then lowered one layer thickness, another layer of material is stuck onto the previous layer and the procedure is repeated with the next cross-section slice of the part. When all cross-section slices have been added, the solid block of material is removed from the platform. The crosshatched areas of the block are then broken away to reveal the final part.

Figure 3 Schematic view of the SLS process

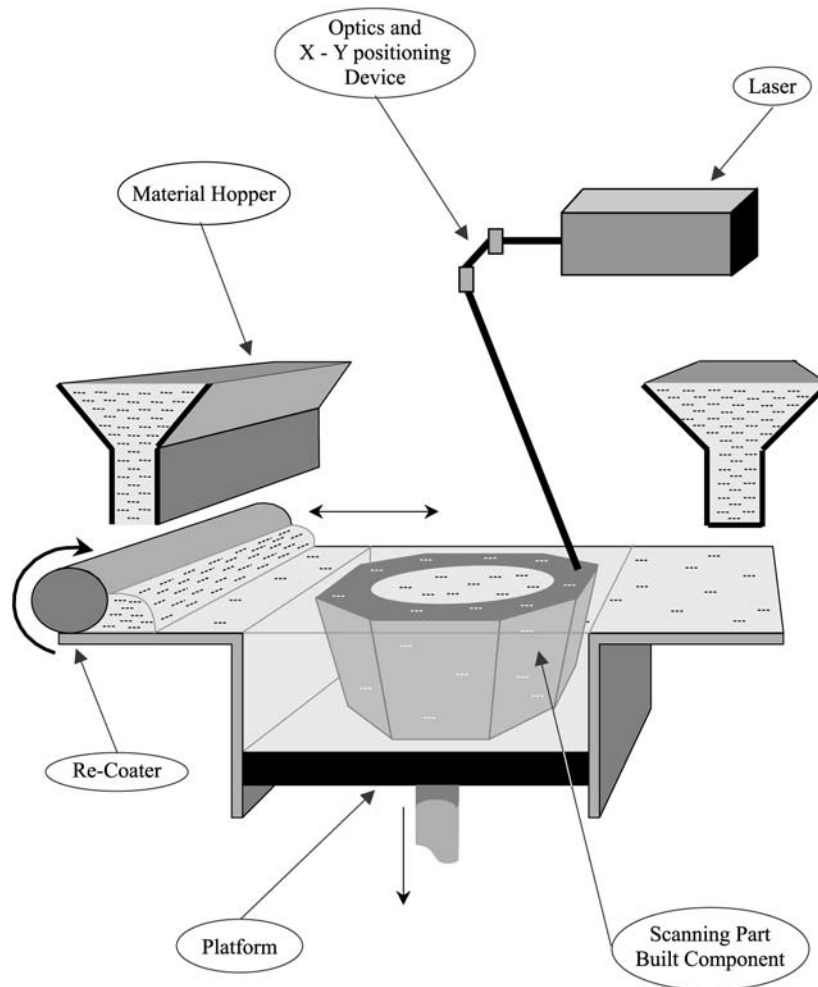


Table III Summary of the LOM process

Materials available	Paper, polyester/polyethylene-based material, ceramic coated paper, polycarbonate composite
Layer thickness	0.080-0.250 mm, 0.111 mm standard
Finishing available	Components can be sealed with varnished and painted or resin impregnation Components can be joined together by gluing, screwing, tapping etc.
Tooling methods available	Sand casting, investment casting, vacuum casting, vacuum forming

4.4.2 Advantages

- Wooden parts can be sanded, drilled and tapped; and
- Large parts can be made quickly and relatively cheaply.

4.4.3 Disadvantages

- Wooden parts with thin cross-section often have poor strength;
- Wooden parts absorb moisture unless the surface is treated;
- Surface finish before post-processing is poor compared to some other RP techniques; and
- Breaking out of parts can be difficult.

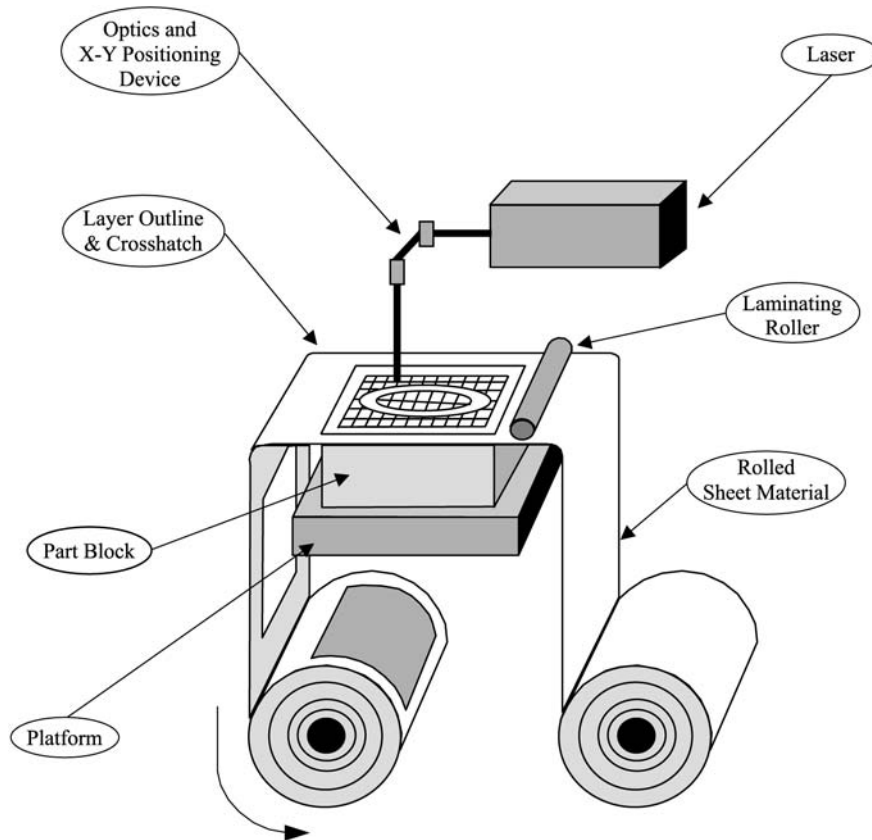
4.4.4 Main suppliers

Helisys Inc. (now defunct) and Kira.

4.5 Fused deposition modelling

Fused deposition modelling (FDM) originally belonged to the class of RP technologies that are collectively known as “concept modellers”. This was because the models created were generally non-functional in terms of their strength, and the surface finish was poor when compared to other technologies such as SL. Over recent years, this has changed as Stratasys have created machines such as the Maxum and Titan. Concept modellers are intended to provide

Figure 4 Schematic view of the LOM process



a fast and clean route to create a part that can be checked for any gross errors, and that can be used as a communication tool between the product development team (Table IV).

4.5.1 Method

A filament of material is extruded out of a fine nozzle and deposited onto a platform. The nozzle moves in the X-Y plane so that the filament is laid down to form a thin cross-sectional slice of the part (Figure 5). The platform is then lowered relative to the nozzle and the next slice of the part is deposited on top of the previous slice. As the extruded filament is hot, it bonds to the material in the previous slice. A second nozzle is used to extrude a different material in order to build-up support structures for the part where needed. Once the part is completed the

support structures must be broken away from the part.

4.5.2 Advantages

- Parts can be made from a variety of materials; and
- Machine can be easily set up and used in an office environment.

4.5.3 Disadvantages

- Support structures are needed;
- Parts have poor strength in the vertical direction;
- Process is slow on parts with large mass; and
- Poor surface finish makes tooling routes unattractive.

4.5.4 Main suppliers

Stratasys Inc.

4.6 Multi-jet modelling

Multi-jet modelling (MJM) also belongs to the class known as “concept modeller”. The MJM technique has been likened to printing in three dimensions and is designed to allow design teams quick access to geometrically acceptable models in a material that would not normally be used for the final part (Table V).

Table IV Summary of the FDM process

Materials available	ABS, elastomer, investment casting wax, polycarbonate
Layer thickness	0.050-0.250 mm
Finishing available	Toluene to smooth and seal the surface
Tooling methods available	Investment casting

Figure 5 Schematic of the FDM process

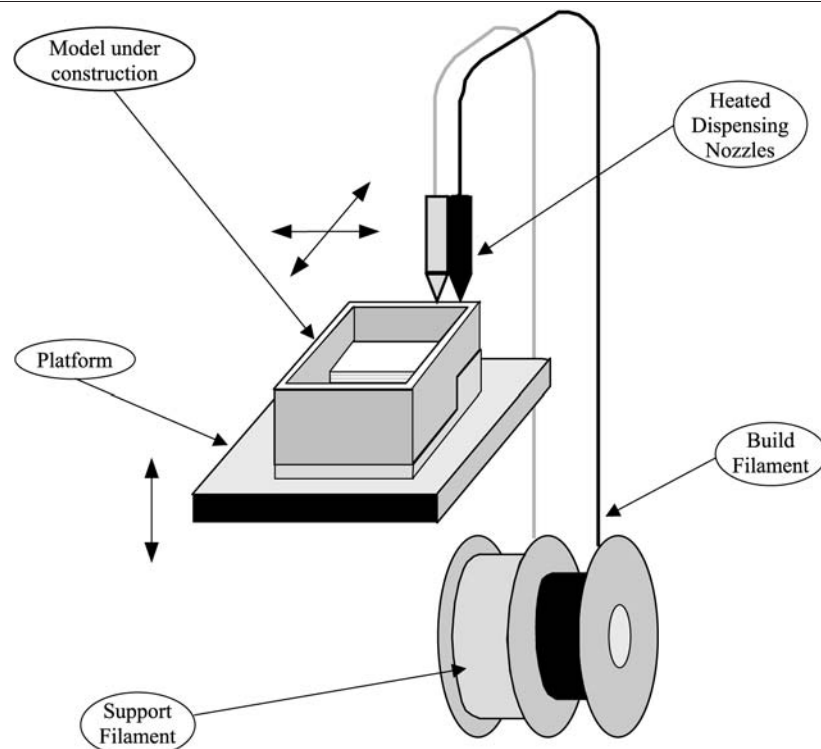


Table V Summary of the MJM process

Materials available	Thermo-plastic
Layer thickness	0.040-0.100 mm
Finishing available	Toluene to smooth the surface
Tooling methods available	Investment casting

4.6.1 Method

A “print head” containing 96* tiny nozzles (or jets) in a linear array passes in the X-Y plane over a platform. Where material is to be deposited, a jet dispenses a droplet of a thermo-plastic polymer (Figure 6). Any number of the 96* jets can be activated simultaneously, giving a rapid dispense rate when all jets are active. The hot droplets of material bond to the previous slice of the part that has just been printed. Thin support pillars must also be built-up slice by slice in the same material where they are needed. When the current slice of the part (plus slice of support pillars) is completed the platform is lowered relative to the print head and the next slice is “printed”. When all the slices have been completed, the part is removed from the machine and the support structure is broken off.

4.6.2 Advantages

- Machine can be used in an office environment; and

- Parts can be obtained quickly by the design team.

4.6.3 Disadvantages

- Support pillars must be broken off and bottom surface finish is very poor;
- Strength of finished parts is poor; and
- Bottom surface finish is pitted, limiting the potential use of investment casting.

4.6.4 Main suppliers

3D Systems (Actua*/ThermoJet).

4.7 Three-dimensional printing

Three-dimensional printing (3DP) is one of the latest modelling techniques. Developed by the Massachusetts Institute of Technology (MIT), the process was subsequently licensed to the Z Corporation for prototyping applications and ProMetal for tooling. 3DP components are typically used as “proof of concept” models however when impregnated appropriately, they can also be used as sacrificial master patterns in the investment casting process (Table VI).

4.7.1 Method

A feed chamber contains a quantity of specially prepared corn starch, the vertical position of the upper surface of the build material can be varied by raising or lowering the feed piston. An adjacent build chamber

Figure 6 Schematic view of the MJM process

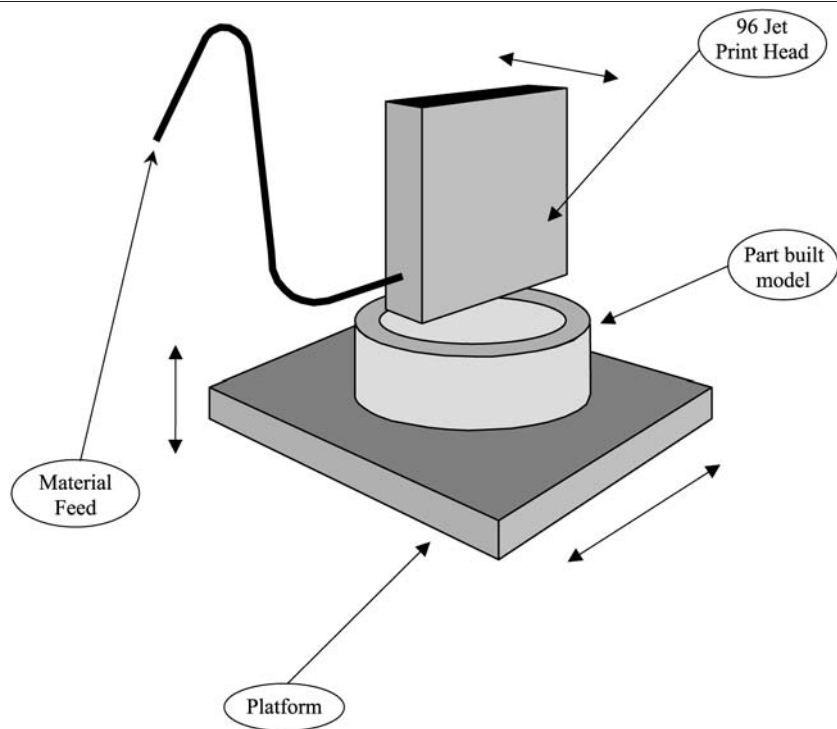


Table VI Summary of the 3DP process

Materials available	Corn starch, plaster
Layer thickness	0.080-0.250 mm
Finishing available	Infiltrated with wax or cyanoacrylate
Tooling methods available	Vacuum casting, investment casting

operates in a similar manner whereby the vertical position of a piston determines the height of the build chamber. A horizontally reciprocating carriage, carrying a feed roller, spreads new material from the feed chamber evenly over the build chamber; excess feed material is swept down an overflow chute. Also mounted on the carriage a “binder cartridge” travels over the surface layer of the build chamber material depositing a binder solution to match the current slice of CAD data (Figure 7). The build piston then descends a predetermined distance, this “layer thickness” can be varied between 0.100 and 0.250 mm; new material is then spread from the feed chamber over the build chamber surface and the printing process is repeated. When all the layers have been printed, the untreated corn starch is cleaned of the component part and the component removed from the build chamber.

4.7.2 Advantages

- Shorter build times when compared to other RP technologies;

- Inexpensive raw materials when compared to other RP technologies; and
- No support structures allow complex geometry to be created.

4.7.3 Disadvantages

- Newly printed parts are fragile and require infiltration; and
- Surface finish is relatively poor.

4.7.4 Main suppliers

Z Corporation and ProMetal.

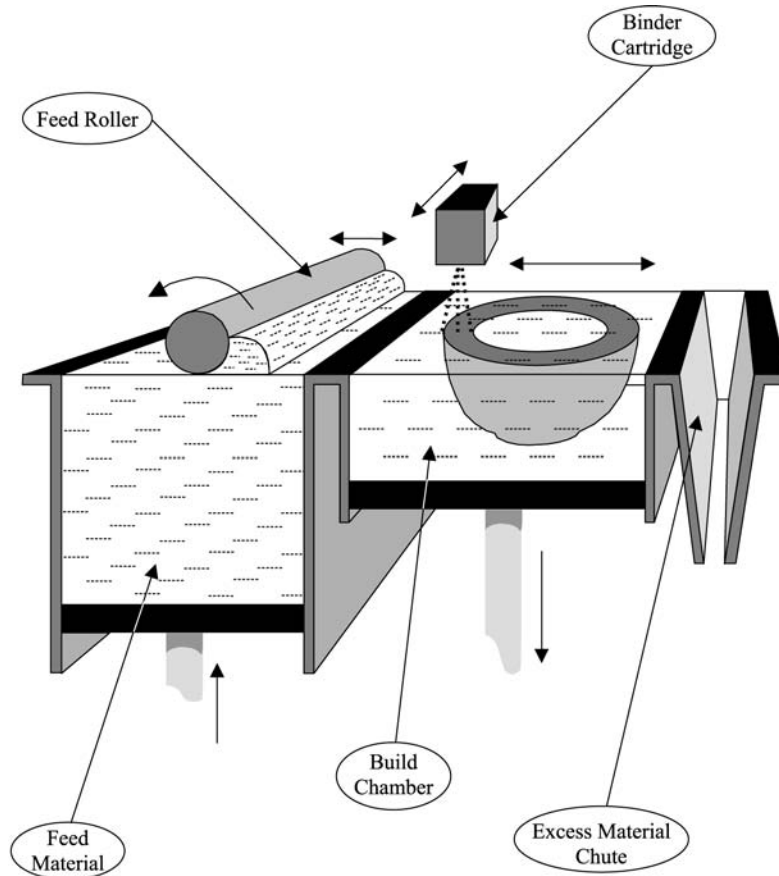
5. Properties of rapid prototype parts

As RP parts are made by additive processes, they can have properties that are quite different from parts that are made by conventional manufacturing processes. It is difficult to compare many properties of RP parts directly, as these depend not only on the material being used, but also on the direction in which the property is being measured. Nevertheless, it is important to have some understanding of the relative properties of parts made by the different RP technologies.

The following paragraphs will assess several key properties namely:

- surface roughness;
- dimensional accuracy; and
- mechanical properties.

Figure 7 Schematic view of the 3DP process



5.1 Surface roughness of RP parts

RP parts are built-up slice by slice, and the surface roughness is affected by three main components (Figure 8).

The *thickness* (h) of each layer of the RP part combined with the build angle of the surface (α) produce a staircase effect as shown. For $\alpha = 90^\circ$ this component of surface roughness will be zero, but for other values of α , the surface roughness will be affected. This thickness component of roughness is essentially independent of the RP technology used.

The end *profile* of each layer then adds a second component of roughness to the surface. This component will depend on the RP technology used to produce the layer.

The material *composition* will then add a third roughness component to the surface. This component will depend on the material used in the RP process and the processing technique.

These three components combine to produce a total that is not easy to predict theoretically, and the surface roughness is best assessed by empirical means as described later.

Staff at the Innovative Manufacturing Centre assessed the surface roughness of RP test piece parts based on the geometry (Figure 9).

The test piece is designed so that the surface roughness can be measured with values of α from 0 to 90° and it produced the following results (Table VII).

Figure 8 Factors that affect the surface roughness of RP parts

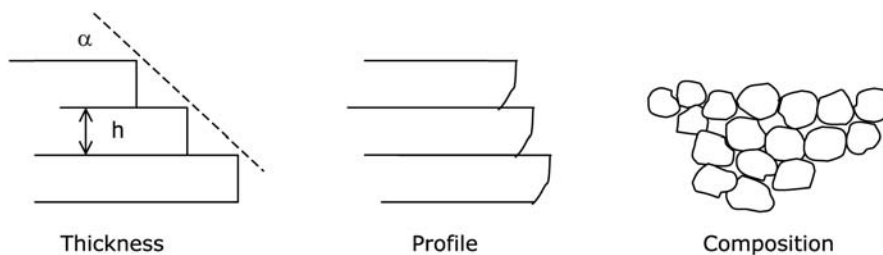


Figure 9 RP surface roughness measurement test piece

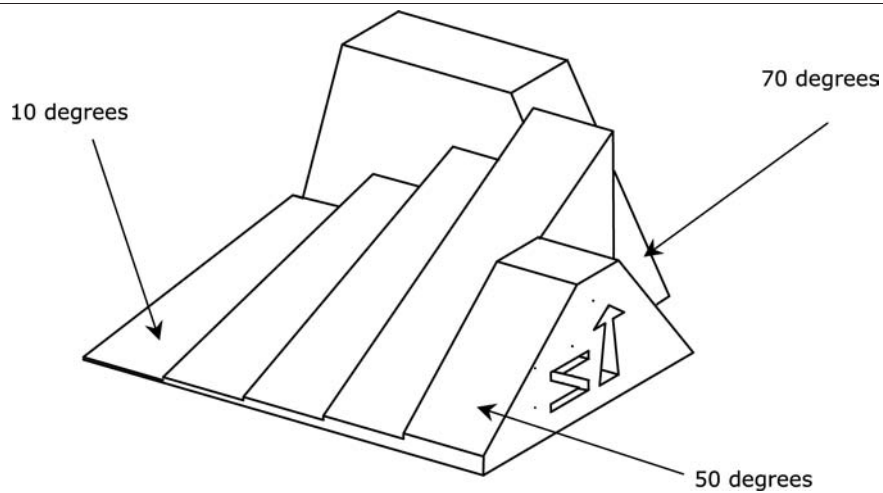


Table VII Surface roughness ($\mu\text{m Ra}$) for selected RP technologies

Technology – material	Layer thickness	Build angle, α /degrees				
		10	30	50	70	90
SLA – Epoxy (ACES style)	0.15	39.9	28.8	21.5	16.7	6.3
SLS – Polystyrene	0.20	65.2	35.6	32.6	24.7	20.6
SLS – Nylon	0.10	28.5	36.9	36.5	39.2	11.8
LOM – Paper	0.10	29.2	27.7	25.3	23.3	16.9
FDM – ABS	0.25	56.6	38.6	26.4	22.7	17.9

It can be seen that there is a considerable variation in surface roughness depending on the technology, layer thickness and material used, and depending on the build angle of the surface. The build angle is particularly important and the RP user must specify which surface of a RP component should have the best surface finish to ensure that the part can be built in the correct orientation to achieve the desired result.

5.2 Dimensional accuracy of RP parts

The same test pieces were also measured to establish the accuracy of linear dimensions for the different RP technologies, when compared to the intended dimensions in the CAD model of the test piece. The results are shown in Table VIII.

As can be seen, the accuracy varies considerably depending on the RP technology used and also on which dimension is being measured. Using this raw data, the average (unweighted) linear dimensional accuracy for the different technologies is detailed in Table IX.

It can be seen that none of the RP technologies considered are more accurate than 97.8 per cent. Although not considered further here, it should also be borne in mind that RP models can also suffer from warpage. The RP user must take the linear dimensional inaccuracy and warpage of RP models into account when considering possible applications for the RP parts.

Table VIII Linear dimensional accuracy of different RP technologies

Technology – material	Intended dimensions from CAD model (mm)						
	34.50	50.35	52.50	56.00	60.00	71.00	75.00
	<i>Actual dimensions of test parts (mm)</i>						
SLA – Epoxy (ACES)	34.83	50.57	52.77	55.85	59.97	70.97	74.94
SLS – Polystyrene	34.43	50.45	52.62	56.48	60.14	71.31	75.12
SLS – Nylon	34.77	50.37	52.59	55.99	60.39	70.65	74.99
LOM – Paper	34.67	50.61	53.20	55.98	59.92	71.05	74.86
FDM – ABS	34.38	50.07	53.45	55.46	60.09	70.42	75.08

Table IX Average linear dimensional accuracy of different RP technologies

Technology – material	Average accuracy over seven dimensions (unweighted) (per cent)
SLA – Epoxy (ACES)	97.7
SLS – Polystyrene	97.7
SLS – Nylon	97.8
LOM – Paper	97.2
FDM – ABS	95.3

5.3 Mechanical properties of RP parts

It is difficult to measure and compare the mechanical properties of RP parts for a number of reasons. The materials and processes used to make the parts are continually improving therefore the mechanical strength and other properties of the parts are also improving. The mechanical properties are also significantly anisotropic, and depend strongly on the direction in which they are tested. Finally, equipment manufacturers are often loath to supply material data for such comparisons and when they do, it is rarely directly comparable with that supplied by other manufacturers. For example, some manufacturers supply data obtained from test parts made on their RP machines, while others supply only data from tests on bulk samples of the source material.

Despite these reservations, it is useful to obtain some feel for the relative order of magnitude of the mechanical properties of the materials used in different RP processes. Table X presents data supplied by the material suppliers or equipment manufacturers themselves.

It should be emphasised, however, that these numbers are only indicative. Users of RP technology should ensure that they fully understand the mechanical properties of their

selected RP process and material combination. This understanding can only be built-up with experience in using the technology.

6. Cost of RP machines

It is not possible to provide a definitive statement of the cost of particular machines as list prices and machine specifications change regularly, however an indication of machine purchase prices is given in Table XI. This table provides approximate prices of machines as sold in the USA in early 1997.

Recent entrants into the RP market place include:

- Z Corporation – 3DP, Z310, 640 in.³, £21,500 (2003)
- Objet – 3DP, Quadra, 960 in.³, \$36,000 (2000)
- Stratasys – FDM, Dimension, 1,000 in.³, £23,000 (2003)
- Stratasys – FDM, Prodigy Plus, 968 in.³, £53,000 (2003)
- Stratasys – FDM, 3000, 1,600 in.³, £69,000 (2003)
- Stratasys – FDM, Titan, 3,584 in.³, £163,000 (2003)

Generally, over the past 5 years, the purchase price of RP equipment has significantly reduced, mainly due to increased competition. This highly competitive market has led to a wealth of faster, more accurate machines, which are arriving with larger build envelopes and a wider range of build materials. This makes the selection of the appropriate RP system a more challenging one, whether it is for purchasing a machine or its prototypes.

Table X Indicative mechanical properties for RP materials

Technology	Material	Tensile strength (MPa)	Elastic modulus (MPa)	Hardness (shore D-scale)
SLA	Epoxy	55-65	2,150-2,600	80-85
	Acrylate	35	1,100-1,200	78
LOM	Paper	26-66	2,524-6,697	55-70
	Polyester	85	3,435	N/A
FDM	ABS	35	2,495	105 Rockwell
	Wax	3.5	277	33
SLS	Fine nylon	36	1,400	N/A
	Acrylic polymer	10	1,100	N/A
	Nylon/50 per cent glass	49	2,828	N/A

Source: Rapid Prototyping Report, July 1997; N/A=not available

Table XI Typical purchase price of RP machines in the USA

Company	Technology	Model	Build volume (in. ³)	Purchase price (US\$)
3D Systems	SLA	SLA 250/30A	1,000	99,000
		SLA 250/40	1,000	145,000
		SLA 250/50	1,000	170,000
		SLA 350/10	2,990	380,000
		SLA 500/40	9,200	490,000
Stratasys	MJM	Actua 2100	640	65,000
	FDM	FDM 1650	1,000	125,000
		FDM 2000	1,000	160,000
Helisys	LOM	FDM 8000	7,776	200,000
		LOM 1015 Plus	2,100	92,000
		LOM 2030H	14,080	255,000
DTM Corp.	SLS	Sinterstation 2000	1,696	300,000
		Sinterstation 2500	3,257	400,000
Sanders Prototype	DODI	ModelMaker – 6PRO	216	59,000
		ModelMaker – II	648	65,000
Cubital	SGC	SGC 4600	2,744	275,000
		SGC 5600	5,600	470,000

Source: Progress Reports from the “RP&M ’97” Conference, Dearborn, April 1997

7. The future of RP

Based on the experiences of staff at the Innovative Manufacturing Centre together with their working relationship with many RP system equipment suppliers, the following areas appear to present the major opportunities for change/development within the RP market place:

- office-based concept modellers will become “standard” PC peripherals;
- laboratory-based systems will reduce their build times by a factor of ten and some processes may, in time, be replaced in total by “office systems”;
- direct tooling processes will become “mainstream” enabling prototype components to be produced in the correct production polymer; and
- metal components will be produced directly by RP techniques.

Over the latter years, one of the largest step changes in RP has been the ability to produce metal components directly. This requirement for “direct metal” led to several major

ventures, investing large amounts of time and money into research and development in this field. Just a handful of the systems which are commercially available or still in the stages of research, include:

- laser engineered net shaping (LENS) by Optomec;
- direct light fabrication (DLF) by Los Alamos National Laboratory;
- controlled metal build-up (CMB) by Fraunhofer IPT;
- direct metal fabrication (DMF) by Rockwell Scientific; and
- direct metal deposition (DMD) by Precision Optical Manufacturing.

As the RP market matures, the opportunities for significant process development step changes will diminish; however, the dynamics of the market together with the general demand for quicker, cheaper and better products will continue to encourage innovative processing solutions that have the capability of “breaking the mould”. Many believe that the journey has only just begun!