UNIT -2

SOLID-BASED RAPID PROTOTYPING SYSTEMS

LAMINATED OBJECT MANUFACTURING (LOM™)

Company

Cubic Technologies was established in December 2000 by Michael Feygin, the inventor who developed Laminated Object Manufacturing® (LOM™). In 1985, Feygin set up the original company, Helisys Inc., to market the LOM™ rapid prototyping machines. However, sales figures did not meet up to expectations [1] and the company ran into financial difficulties. Helisys Inc. subsequently ceased operation in November 2000. Currently, Cubic Technologies, the successor to Helisys Inc., is the exclusive manufacturer of the LOM™ rapid prototyping machine. The company's address is Cubic Technologies Inc., 100E, Domingnez Streets, Carson, California 90746-3608, USA.

Models and Specifications

Cubic Technologies offers two models of LOM™ rapid prototyping systems, the LOM-1015Plus™ and LOM-2030H™ (see Figure 4.1). Both these systems use the CO_2 laser, with the LOM-1015Plus™ operating a 25 W laser and the LOM-2030H™ operating a 50 W laser. The optical system, which delivers a laser beam to the top surface of the work, consists of three mirrors that reflect the CO_2 laser beam and a focal lens that focuses the laser beam to about 0.25 mm (0.010"). The control of the laser during cutting is by means of a *XY* positioning table that is servo-based as opposed to the galvanometer mirror system. The LOM-2030H™ is a larger machine and produces larger prototypes. The work volume of the LOM-2030H™ is 810 mm × 550 mm × 500 mm (32" × 22" × 20") and that of the LOM-1015Plus™ is 380 mm × 250 mm × 350 mm (15" × 10" × 14"). Detailed specifications of the two machines are summarized in Table 4.1.

Model	LOM-1015Plus™	LOM-2030H™
Max. part envelope size, mm (in)	L381 × W254 × H356 (L15 × W10 × H14)	L813 × W559 × H508 (L32 × W22 × H20)
Max. part weight, kg (lbs)	32 (70)	204 (405)
Laser, power and type	Sealed 25 W, CO_2 Laser	Sealed 50 W, CO_2 Laser
Laser beam diameter, mm (in)	0.20–0.25 (0.008–0.010)	0.203–0.254 (0.008–0.010)
Motion control	Servo-based *X–Y* motion systems with a speed up to 457 mm/sec (18"/sec); Typical *Z*-platform feedback for motion system	Brushless servo-based *X–Y* motion dystems with a speed up to 457 mm/sec (18"/sec); Typical *Z*-platform feedback for motion system
Part accuracy *XYZ* directions, mm (in)	±0.127 mm (±0.005 in)	±0.127 mm (±0.005 in)
Material thickness,	0.08–0.25,	0.076–0.254,

mm (in)	(0.003–0.008)	(0.003–0.008)
Material size	Up to 356 mm (14") roll width and roll diameter	Up to 711 mm (28") roll width and roll diameter
Floor space, m (ft)	3.66 × 3.66 (12 × 12)	4.88 × 3.66 (16 × 12)
Power	Two (2) 110VAC, 50/60 Hz, 20 Amp, single phase Two (2) 220VAC, 50/60 Hz, 15 Amp, single phase	220VAC, 50/60 Hz, 30 Amp, single phase
Materials	LOMPaper® LPH series, LPS series LOMPlastics® LPX series	LOMPaper® LPH series, LPS series LOMPlastics® LPX series, LOMComposite® LGF series

Principle

The LOM™ process is based on the following principles:

Parts are built, layer-by-layer, by laminating each layer of paper or other sheet-form materials and the contour of the part on that layer is cut by a CO_2 laser.

Each layer of the building process contains the cross-sections of one or many parts. The next layer is then laminated and built directly on top of the laser-cut layer.

The *Z*-control is activated by an elevation platform, which lowers when each layer is completed, and the next layer is then laminated and ready for cutting. The *Z*-height is then measured for the exact
Height so that the corresponding cross sectional data can be calculated for that layer.

No additional support structures are necessary as the "excess" material, which are cross-hatched for later removal, act as the support.

Process

The patented Laminated Object Manufacturing® (LOM™) process [2–4] is an automated fabrication method in which a 3D object is constructed from a solid CAD representation by sequentially laminating the part cross-sections. The process consists of three phases: pre-processing; building; post-processing

Pre-processing

The pre-processing phase comprises several operations. The initial steps include generating an image from a CAD-derived STL file of the part to be manufactured, sorting input data, and creating secondary data structures. These are fully automated by LOMSlice™, the LOM™ system software, which calculates and controls the slicing functions. Orienting and merging the part on the LOM™ system are done manually. These tasks are aided by LOMSlice™, which provides a menu-driven interface to perform transformations (e.g., translation, scaling, and mirroring) as well as merges.

Building

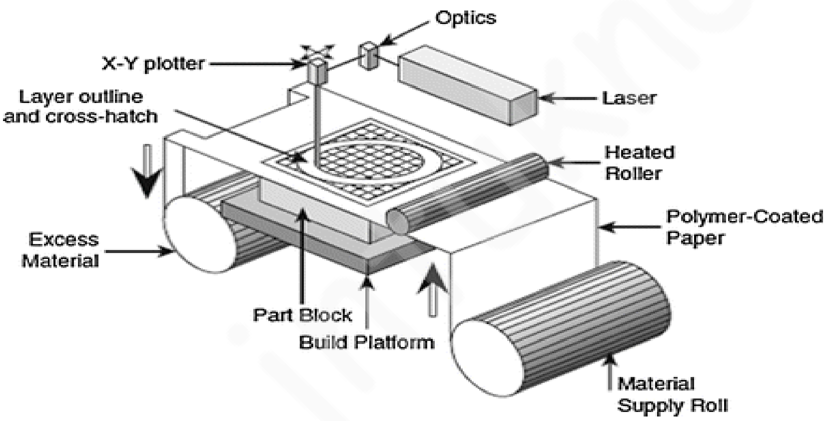
In the building phase, thin layers of adhesive-coated material are sequentially bonded to each other and individually cut by a CO_2 laser beam (see Figure 4.2). The build cycle has the following steps:

LOMSlice™ creates a cross-section of the 3D model measuring the exact height of the model and slices the horizontal plane accordingly. The software then images crosshatches which define the outer perimeter and convert these excess materials into a support structure.

The computer generates precise calculations, which guide the focused laser beam to cut the cross-sectional outline, the cross-hatches, and the model's perimeter. The laser beam power is designed to cut exactly the thickness of one layer of material at a time. After the perimeter is burned, everything within the model's boundary is "freed" from the remaining sheet.

The platform with the stack of previously formed layers descends and a new section of material advances. The platform ascends and the heated roller laminates the material to the stack with a single reciprocal motion, thereby bonding it to the previous layer.

Fig 2.1 **LOM building** process (Courtesy Cubic Technologies Inc.)



The vertical encoder measures the height of the stack and relays the new height to LOMSlice™, which calculates the cross section for the next layer as the laser cuts the model's current layer.

This sequence continues until all the layers are built. The product emerges from the LOM™ machine as a completely enclosed rectangular block containing the part.

Post-processing

The last phase, post-processing, includes separating the part from its support material and finishing it. The separation sequence is as follows [see Figures 2.2 (a) – 2.2(d)]:

The metal platform, home to the newly created part, is removed from the LOM™ machine. A forklift may be needed to remove the larger and heavier parts from the LOM-2030H™.

Normally a hammer and a putty knife are all that is required to separate the LOM™ block from the platform. However, a live thin wire may also be used to slice through the double-sided foam tape, which serves as the connecting point between the LOM™ stack and the platform.

The surrounding wall frame is lifted off the block to expose the crosshatched pieces of the excess material. Crosshatched pieces may then be separated from the part using wood carving tools.

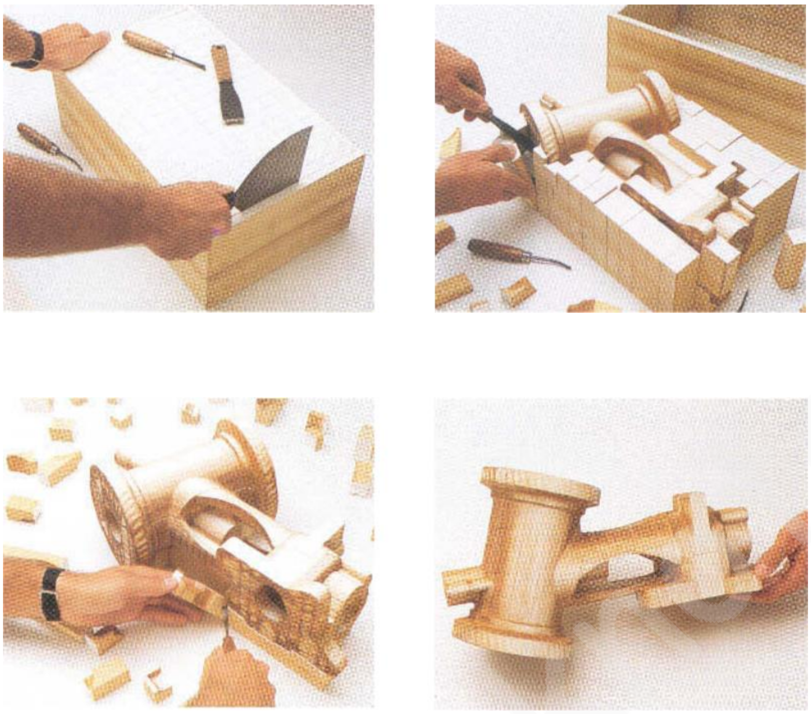


Figure 2.2: Separation of the LOM™ object
The laminated stack is removed from the machine's elevator plate.
The surrounding wall is lifted off the object to expose cubes of excess material.
Cubes are easily separated from the object's surface.
The object's surface can then be sanded, polished or painted, as desired.

After the part is extracted from surrounding crosshatches the wood-like LOM™ part can be finished. Traditional model-making finishing techniques, such as sanding, polishing, painting, etc. can be applied. After the part has been separated it is recommended that it be sealed immediately with urethane, epoxy, or silicon spray to prevent moisture absorption and expansion of the part. If necessary, LOM™ parts can be machined — by drilling, milling and turning.

System Structure

The LOM-1015Plus™ and LOM-2030H™ have a similar system structure which can be broken down into several subsystems: computer hardware and software, laser and optics, *X–Y* positioning device, platform and vertical elevator, laminating system, material supply and take-up.

The computer is an IBM-compatible PC. The LOM™ software, LOMSlice™, is a true 32-bit application with a user-friendly interface including menus, dialog boxes and progress indicators. LOMSlice™ is completely integrated, providing preprocessing, slicing, and machine control within a single program. *Z*-dimension accuracy is maintained through a closed loop real-time feedback mechanism and is calculated upon each lamination. As the laser is cutting the model, software is simultaneously planning the next layer's outline and crosshatches.

Lamination is accomplished by applying heat and pressure by way of rolling a heated cylinder across the sheet of material, which has a thin layer of a thermoplastic adhesive on one side. Studies [6] have indicated that interlaminate strength of LOM™ parts is a complex function of bonding speed, sheet deformation, roller temperature, and contact area between the paper and the roller. By increasing pressure of the heated roller, lamination is improved due to fewer air bubbles. Increased pressure also augments the contact area thereby bolstering interlaminate strength. Pressure is controlled by the limit switch which is mounted on the heated roller. If compression is set too high it can cause distortion in the part

Materials

Potentially, any sheet material with adhesive backing can be utilized in Laminated Object Manufacturing. It has been demonstrated that plastics, metals, and even ceramic tapes can be used. However, the most popular material has been Kraft paper with a polyethylene-based heat seal adhesive system because it is widely available, cost-effective, and environmentally benign [7].

In order to maintain uniform lamination across the entire working envelope it is critical that the temperature remain constant. A temperature control system, with closed-loop feedback, ensures the system's temperature remains constant, regardless of its surrounding environment.

Advantages of LOM

Wide variety of materials. In principle, any material in sheet form can be used in the LOM™ systems. These include a wide variety of organic and inorganic materials such as paper, plastics, metals, composites and ceramics. Commercial availability of these materials allow users to vary the type and thickness of manufacturing materials to meet their functional requirements and specific applications of the prototype.

Fast build time. The laser in the LOM™ process does not scan the entire surface area of each cross-section, rather it only outlines its periphery. Therefore, parts with thick sections are produced just as quickly as those with thin sections, making the LOM™ process especially advantageous for the production of large and bulky parts.

High precision. The feature to feature accuracy that can be achieved with LOM™ machines is usually better than 0.127 mm (0.005"). Through design and selection of application specific parameters, higher accuracy levels in the X–Y and Z dimensions can be achieved. If the layer does shrink horizontally during lamination, there is no actual distortion as the contours are cut post-lamination, and laser cutting itself does not cause shrinkage. If the layers shrink in the transverse direction, a closed-loop feedback system gives the true cumulative part height upon each lamination to the software, which then slices the 3D model with a horizontal plane at the appropriate location.

Support structure. There is no need for additional support structure as the part is supported by its own material that is outside the periphery of the part built. These are not removed during the LOM™ process and therefore automatically act as supports for its delicate or overhang features.

Post-curing. The LOM™ process does not need to convert expensive, and in some cases toxic, liquid polymers to solid plastics or plastic powders into sintered objects. Because sheet materials are not subjected to either physical or chemical phase changes, the finished LOM™ parts do not experience warpage, internal residual stress, or other deformations.

Disadvantages of using LOM

Precise power adjustment. The power of the laser used for cutting the perimeter (and the crosshatches) of the prototype needs to be precisely controlled so that the laser cuts only the current layer of lamination and not penetrate into the previously cut layers. Poor control of the cutting laser beam may cause distortion to the entire prototype.

Fabrication of thin walls. The LOM^{TM} process is not well suited for building parts with delicate thin walls, especially in the *Z*-direction. This is because such walls usually are not sufficiently rigid to withstand the post-processing process when the cross-hatched outer perimeter portion of the block is being removed. The person performing the post-processing task of separating the thin wall of the part from its support must be fully aware of where such delicate parts are located in the model and take sufficient precautions so as not to damage these parts.

Integrity of prototypes. The part built by the LOM^{TM} process is essentially held together by the heat sealed adhesives. The integrity of the part is therefore entirely dependent on the adhesive strength of the glue used, and as such is limited to this strength. Therefore, parts built may not be able to withstand the vigorous mechanical loading that the functional prototypes may require.

Removal of supports. The most labor-intensive part of the LOM^{TM} process is its last phase of post-processing when the part has to be separated from its support material within the rectangular block of laminated material. This is usually done with wood carving tools and can be tedious and time consuming. The person working during this phase needs to be careful and aware of the presence of any delicate parts within the model so as not to damage it.

Applications of LOM

Visualization. Many companies utilize LOM^{TM}'s ability to produce exact dimensions of a potential product purely for visualization. LOM^{TM} part's wood-like composition allows it to be painted or finished as a true replica of the product

Form, fit and function. LOM^{TM} parts lend themselves well for design verification and performance evaluation

Manufacturing. The LOM^{TM} part's composition is such that, based on the sealant or finishing products used, it can be further tooled for use as a pattern or mold for most secondary tooling techniques including: investment casting, casting, sanding casting, injection molding, silicon rubber mold, vacuum forming and spray metal molding.

Rapid tooling. Two part negative tooling is easily created with LOM^{TM} systems. Since the material is solid and inexpensive, bulk complicated tools are cost effective to produce.

FUSED DEPOSITION MODELING (FDM)

Company

Stratasys Inc. was founded in 1989 and has developed most of the company's products based on the Fused Deposition Modeling (FDM) technology. The technology was first developed by Scott Cramp in 1988 and the patent was awarded in the U.S. in 1992. FDM uses the extrusion process to build 3D models. Stratasys introduced its first rapid prototyping machine, the 3D modeler® in early 1992 and started shipping the units later that year. Over the past decade, Stratasys has grown progressively, seeing her rapid prototyping machines' sales increase from six units in the beginning to a total of 1582 units in the year 2000 [9]. The company's address is Stratasys Inc., 14950 Martin Drive, Eden Prairie, MN 55344-202, USA.

Models and Specifications

Stratasys has developed a series of rapid prototyping machines and also a wide range of modeling materials to cater to various industries' needs. The company's rapid prototyping systems can be broadly classified into two categories, the FDM series and the concept modeler. The FDM series include models like FDM 3000, FDM Maxum and FDM Titan. The concept modeler series includes models like Dimension and Prodigy Plus. A summary of the product specifications

Models	FDM 3000	FDM Maxum	FDM Titan
Technology	FDM		
Build size, mm (in)	Parts up to 254 × 254 × 406 (10 × 10 × 16)	Parts up to 600 × 500 × 600 (23 × 19.7 × 23)	Parts up to 355 × 406 × 406 (14 × 16 × 16)
Accuracy, mm (in)	± 0.127 (± 0.005)	Up to 127 mm (5 in): ± 0.127 (± 0.005) Greater than 127 mm (5 in) ± 0.038 mm/mm (± 0.0015 in/in)	
Layer road width, mm (in)	0.250 to 0.965 (0.010 to 0.038)	0.305 to 0.965 (0.012 to 0.038)	Not available
Layer thickness, mm (in)	0.178 to 0.356 (0.007 to 0.014)	0.178 to 0.356 (0.007 to 0.014)	0.25 (0.010)
Support structures	Automatically generated with SupportWorks software; WaterWorks or Support System (BASS)	Automatically generated with Insight software; WaterWorks soluble support system	
Size, $w \times h \times d$, mm (in)	660 × 1067 × 914 (26 × 42 × 36)	2235 × 1981 × 1118 (88 × 78 × 44)	1270 × 1981 × 876 (50 × 78 × 34.5)
Weight, kg (lbs)	160 (350)	1134 (2500)	726 (1600)
Power requirements	208–240 VAC, 50/60 Hz, 10 A 110–120 VAC, 60 Hz, 20 A	208–240 VAC, 50/60 Hz, 32 A single phase (min. 50 A dedicated service)	230 V, 50/60 Hz, 3 phase, 16 A/phase (min. 20 A dedicated service)
Modeling materials	ABS (White), ABSi, Investment Casting Wax,	ABS (white)	ABS, Polycarbonate, Polyphenyl-sulfone

	Elastomer		
Software	QuickSlice® and Support-Works™	Insight	Insight

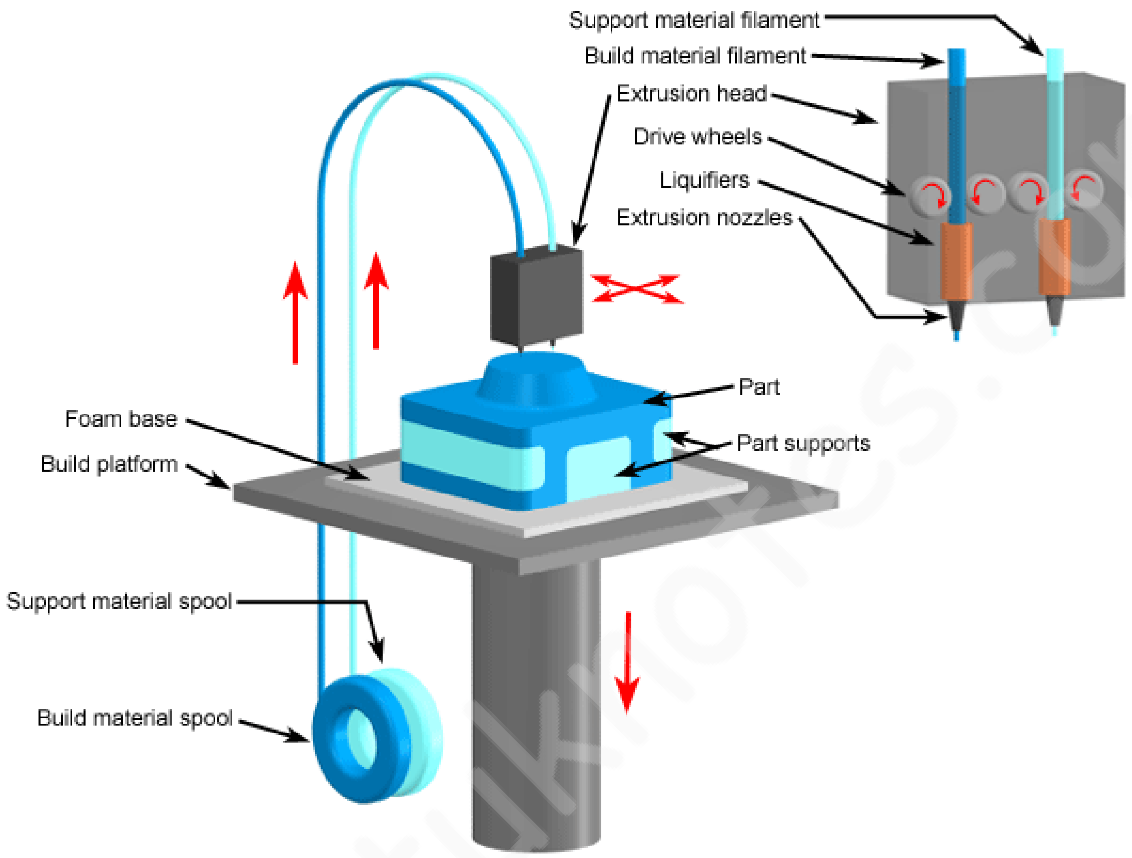
Model	Dimension	Prodigy Plus
Technology	3D printing base on FDM	FDM
Build size, mm (in)	305×203×203(12×8×8)	203×203×305(8×8×12)
Accuracy, mm (in)	± 0.127 (± 0.005)	± 0.127 (± 0.005)
Layer thickness mm (in)	“Standard” — 0.245 (0.010) “Draft” — 0.33 mm (0.013)	User selectable: “Fine” — 0.178 mm (0.007) “Standard” — 0.245 (0.010) “Draft” — 0.33 mm (0.013)
Automatic operation	Easy to use Catalyst™ software imports STL files and automatically slices the model, creates any necessary support structures and generates build files	Catalyst™ software automatically imports and slices STL files, orients the part, generates soluble support structures (if necessary), and creates the deposition path to build parts
Size, *w* × *d* × *h*, mm (in)	914 × 686 × 1041 (36 × 27 × 41)	864 × 686 × 1041 (34 × 27 × 41)
Weight, kg (lbs)	136 (300)	128 (282)
Power requirements	220–240 VAC, 50/60 Hz, 6 A or 110–120 VAC, 60 Hz, 12 A	110–120 VAC, 60 Hz, 15 A max. or 220–240 VAC, 50/60 Hz, 7 A max
Materials	ABS plastic in white (standard), blue, yellow, black, red or green. Custom colors available	
Material supply	One autoload cartridge with 950 cu. cm. (58 cu. in.) ABS material and one autoload cartridge with 950 cu. cm. (58 cu. in.) support material	One autoload cartridge with 950 cu. cm. (58 cu. in.) ABS material and one autoload cartridge with 950 cu. cm. (58 cu. in.) soluble support material

Principle

The principle of the FDM is based on surface chemistry, thermal energy, and layer manufacturing technology. The material in filament (spool) form is melted in a specially designed head, which extrudes on the model. As it is extruded, it is cooled and thus solidifies to form the model. The model is built layer by layer, like the other RP systems. Parameters which affect performance and functionalities of the system are material column strength, material flexural modulus, material viscosity, positioning accuracy, road widths, deposition speed, volumetric flow rate, tip diameter, envelope temperature, and part geometry.

Process

In this patented process [12], a geometric model of a conceptual design is created on a CAD software which uses IGES or STL formatted files. It can then imported into the workstation where it is processed through the QuickSlice® and SupportWork™ propriety software before loading to FDM 3000 or similar systems. For FDM Maxum and Titan, a newer software known as Insight is used. The basic function of Insight is similar to that of QuickSlice® and the only difference is that Insight does not need another software to auto-generate the supports. The function is incorporated into the software itself. Within this software, the CAD file is sliced into horizontal layers after the part is oriented for the optimum build position, and any necessary support structures are automatically detected and generated. The slice thickness can be set manually to anywhere between 0.172 to 0.356 mm (0.005 to 0.014 in) depending on the needs of the models. Tool paths of the build process are then generated which are downloaded to the FDM machine.



The modeling material is in spools — very much like a fishing line. The filament on the spools is fed into an extrusion head and heated to a semi-liquid state. The semi-liquid material is extruded through the head and then deposited in ultra-thin layers from the FDM head, one layer at a time. Since the air surrounding the head is maintained at a temperature below the materials' melting point, the exiting material quickly solidifies. Moving on the *X–Y* plane, the head follows the tool path generated by QuickSlice® or Insight generating the desired layer. When the layer is completed, the head moves on to create the next layer. The horizontal width of the extruded material can vary between 0.250 to 0.965 mm depending on model. This feature, called "road width", can vary from slice to slice. Two modeler materials are dispensed through a dual tip mechanism in the FDM machine. A primary modeler material is used to produce the model geometry and a secondary material, or release material, is used to produce the support structures. The release material forms a bond with the primary modeler material and can be washed away upon completion of the 3D models.

Advantages of using FDM technology

Fabrication of functional parts. FDM process is able to fabricate prototypes with materials that are similar to that of the actual molded product. With ABS, it is able to fabricate fully functional parts that have 85% of the strength of the actual molded part.

Minimal wastage. The FDM process build parts directly by extruding semi-liquid melt onto the model. Thus only those material needed to build the part and its support are needed, and material wastages are kept to a minimum. There is also little need for cleaning up the model after it has been built.

Ease of support removal. With the use of Break Away Support System (BASS) and WaterWorks Soluble Support System, support structures generated during the FDM building process can be easily broken off or simply washed away

Ease of material change. Build materials, supplied in spool form (or cartridge form in the case of the Dimension or Prodigy Plus), are easy to handle and can be changed readily when the materials in the system are running low. This keeps the operation of the machine simple and the maintenance relatively easy

Disadvantages of using FDM technology

Restricted accuracy. Parts built with the FDM process usually have restricted accuracy due to the shape of the material used, i.e., the filament form. Typically, the filament used has a diameter of 1.27 mm and this tends to set a limit on how accurately the part can be built.

Slow process. The building process is slow, as the whole cross-sectional area needs to be filled with building materials. Building speed is restricted by the extrusion rate or the flow rate of the build material from the extrusion head. As the build material used are plastics and their viscosities are relatively high, the build process cannot be easily speeded up.

Unpredictable shrinkage. As the FDM process extrudes the build material from its extrusion head and cools them rapidly on deposition, stresses induced by such rapid cooling invariably are introduced into the model. As such, shrinkages and distortions caused to the model built are a common occurrence and are usually difficult to predict, though with experience, users may be able to compensate for these by adjusting the process parameters of the machine.

Applications of FDM Processes

Models for conceptualization and presentation. Models can be marked, sanded, painted and drilled and thus can be finished to be almost like the actual product.

Prototypes for design, analysis and functional testing. The system can produce a fully functional prototype in ABS. The resulting ABS parts have 85% of the strength of the actual molded part. Thus actual testing can be carried out, especially with consumer products.

Patterns and masters for tooling. Models can be used as patterns for investment casting, sand casting and molding.