Commercially Available Layered Manufacturing Techniques: A Review

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Abstract

Generative manufacturing answers the need of manufacturing which is environment friendly and the process is carried out without wastage of material. A large number of commercially viable GM techniques are available in the market today. The paper compares these processes on the basis of working principles, build mechanism, performance characteristics. This paper attempts to review the various layered manufacturing techniques. Through this paper an attempt has been made to study the various LM techniques with a view to select the process based on application requirements.

Keywords - Generative/ Additive/ Layered/ Rapid Manufacturing, Rapid Prototyping, RP Techniques, Comparative Evaluation

Introduction

Generative manufacturing answers the need of manufacturing which is environment friendly and the process is carried out without wastage of material (Dutta *et al*., 2013; Wohler *et al.*, 2013). A large number of commercially viable GM techniques are available in the market today but no objective assessment technique is available to select the process. An attempt has been made to review and compare few most successful GM processes on the basis of working principles, build mechanism and performance characteristics with a view to select the process based on application requirements. This work attempts to compare the processes with a view to provide inputs that may aid selection of particular layered manufacturing process.

Classification of GM/RP processes

The most common way of classifying materials is on the basis of state of the raw material for prototyping requirements. The state may be liquid, powder or solid sheets (Kruth *et al*.,1991). Another basis of classification can be the mechanism employed to transfer sliced data into the physical structures. Following this, GM processes fall into four categories namely-one dimensional channel, multiple one dimensional channels, array of one dimensional channels and two dimensional channel (Pham *et al.,* 2003). Third approach can be to classify the processes on the basis of underlying technology like lasers, printers or extrusion, etc. (Gibson *et al.,* 2010).Better approach would be to incorporate first two basis together (Pham *et al.,* 2003; Gibson *et al.,* 2010). Figure 3.1 shows such classification by taking into account both the raw material state and the data transfer mechanism employed.

The empty boxes in this array can provide a foundation to researchers and industry personnel for further advancements in this field**.**

		Mechanism of Data Transfer			
		One Dimensional	**Multiple One Dimensional**	**One Dimensional array**	**Two Dimensional**
State of Raw Material	**Liquid**	Stereo lithography, Liquid Thermal Polymerization		Objet Quadra Process	Solid Ground Curing, Rapid Micro Product Development, Holographic Interference Solidification
	Discrete particles	Selective Laser Sintering, Laser sintering Technology, Laser Engineering Net Shaping, Laser assisted chemical Vapor deposition, Selective laser reactive sintering, Gas phase deposition, Selective area laser deposition	Laser Sintering Technology	Three Dimensional Printing	Direct Photo Shaping
	Molten Material	Fused Deposition Modelling, Ballistic particle manufacture, Three dimensional welding, Precision droplet based Net-form Manufacturing		Multi Jet Modelling	Shape Deposition Modelling
	Solid Sheets	Laminated object manufacturing, Paper lamination Technology			Solid Foil Polymerization
	Electoset Fluids				Electro Setting

Figure 1: Classification of GM/RP processes.

Description Parameters

Nine commercially available and successful GM processes are described with respect to their commercial details, working principles, schematic diagrams, build mechanism and performance characteristics (Gogate *et al.*, 2012).

Build Mechanism

The build mechanism encompasses five aspects including state of raw material, type of energy source, layer construction method, condition of completed part and part geometry. The effects of these aspects are included in Table 1.

Table 1: Effects of various aspects of Build Mechanism

State of raw material	The type of energy source	Layer construction method	Condition of completed part	Part Geometry
1)Achievable part accuracy 2)Surface quality 3) Building time 4) Building cost 5) Post operation	1) Achievable part accuracy 2) Surface finish 3) Build cost	1)Building accuracy 2) Building cost	Amount of post processing work	1) Building time 2) Building cost 3)Dimensional accuracy 4) Surface Quality

Performance Characteristics:

These encompass three main issues namely dimensional accuracy, surface finish and build time utilized.

A) Dimensional Accuracy which is a function of –

1) Technician's skill and experience 2) Process capability 3) Dimensional variation.

B) Surface finish which is a function of -

1) Process being used 2) Building orientation 3) Layer Thickness 4) Building Style

5) Accuracy of scanning 6) Material Deposition System 7) Material Used

C) Building Time which is the sum of -

1) Data Preparation Time

i) Data transfer, Data conversion, Part orientation and slicing, sliced data sorting, parameter setting, path generation, design and slicing of external support(if any) together constitute the data preparation time.

ii) It is same for all the rapid prototyping processes.

2) Fabrication Time

Sum of formation time for the solid volume and the delay between the formations of layer.

$T_f=n.t_w+(V_{part}/L)/\gamma_f+(V_{supply}/L)/\gamma_{supply}$

tw - delay between layers γ_f-solidifying rate for part geometry in XY plane

(V_{part}/L)-total section area needed to be solidified γ_{supply}-solidification

3) Post Processing Time

i) Parts build from different RP processes have different requirements of post processing; techniques; geometrical complexity.

ii) Cleaning +post curing + finishing

iii) P.P.T in

SL –removing liquid resin, removing support, post curing, sand finishing (tentatively)

SLS-Removing powder, polymer infiltration (T), drying (T), sand finishing (T)

FDM-support removal, finishing (T)

LOM-removing redundant material, sand finishing (T)

Extensive study of commercially viable LM Techniques

Stereo Lithography Apparatus

A) Company- 3D System Inc. (founded by Charles W. Hull)

B) Year of manufacture-1986

C) Commercial models available- llios HD by OS-RC, Form 1 by Form labs and the Pegasus Touch by FSL3D

D) Working Principle

It involves slicing of 3D CAD models into 2D cross-sections. Thereafter, the elevator is positioned at programmed height resin layer is deposited. The optical system focused with the required resolution and the layer dimensions are selected. Then, the light source is activated and is exposed with programmed intensity and time. All the layers are completed and the model is removed thereafter (Bartolo *et al.*, 2011).

E) Schematic diagram

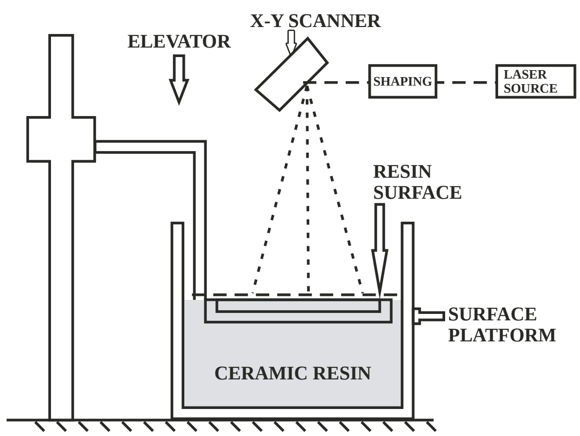

Figure 2: Schematic diagram of Stereo Lithography apparatus

F) Build Mechanism

F.1 Raw Material – SLA uses Photopolymer in liquid state (for e.g., epoxy based elastomers, polypropylene).

F.2 Energy Source - Energy source used is swinging laser along with ultraviolet light which cures the resin. High laser power isn't required because the curing process is mainly initialized by photons.

F.3 Layer Construction – 2D sections are constructed via photocurrent solidification.

F.4 Condition of Completed Part- Completed part is immersed in a fluid (liquid) that provides little support for the overhanging area or floating components.

G) Performance Characteristics

G.1 Dimensional Accuracy- Accuracy is affected by form errors, dimensional errors and surface roughness of manufactured parts. Dimensional accuracy in the z direction is observed to be significant compared to other directions.

G.2 Surface Finish-Surfaces close to the horizontal plane has poor finish due to the layer stepping effect. Surface roughness (Ra) value lies approximately around 10 micrometer.

G.3 Build Time-A large number of facets can be used to improve the dimensional accuracy but it will increase the build time.

Selective Layer Sintering

A) Company- University of Texas at Austin. (Founded by Dr. Carl Deckard)

B) Year of manufacture- mid 1980s

C) Commercial models available – ProX™, sPro™ 140, sPro™230, sPro™60 HD, etc

D) Working Principle-

It uses a CO_2 laser of power 25-50 W. This process uses fine powder which is heated such that grains overcome the surface tension and fuse together. To minimize thermal distortion, the bed is heated below melting point of material; this also allows fusion with previous layer. The powder feed chamber moves upwards and the bed is lowered. A counter rotating roller spreads the new layer. The unsintered material forms the support and the sintered one forms the layer. The support is later removed, cleaned and washed away.

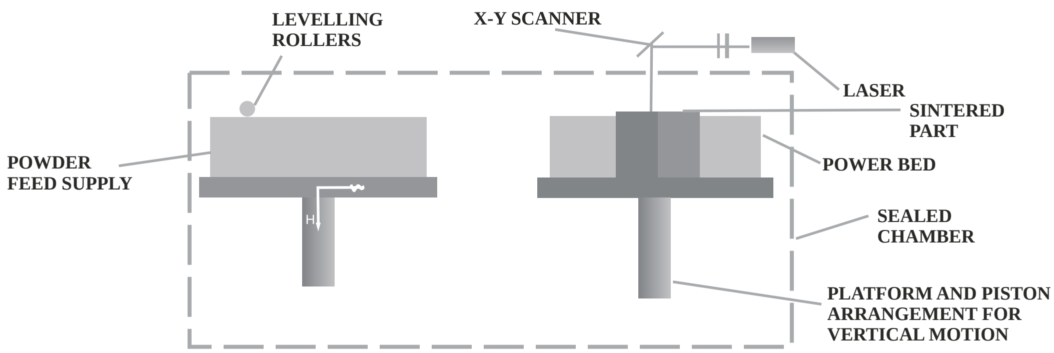

Figure 3: Schematic Diagram of Selective Laser Sintering Apparatus.

F) Build Mechanism

F.1 Raw material - Plastic and metal powders

F.2 Energy Source - Laser provides heat to fuse selected regions of powder which requires high laser power to sinter the plastic/metal powders.

F.3 Layer Construction-2D sections are constructed via laser sintering.

F.4 Condition of Completed Part- Parts built are buried in powder which provides natural support for overhanging in a part.

G) Performance Characteristics –

G.1 Dimensional Accuracy - Smaller particles also sinter much faster when trapped inside scaffold pores and at boundaries of designed features causing dimensional inaccuracy.

G.2 Surface Finish - Surface quality of the sintered parts depend on the high inertia of the beam delivery system. Because of high wear resistance and hardness while dealing with extremely hard powders, the finish cannot be improved by grinding or polishing. Surface finish can be improved by use of fine powder.

G.3 Build Time - Roller speed affects the build time inversely in general.

Laminated Object Manufacturing

A) Company- Helisys Inc. (Cubic Technologies)

B) Year of manufacture-1980s

C) Commercial models available- Helisys, type 1015plus (paper), 3D system (plastic).

D) Working Principle-

Slices are cut using a 25-50 watt CO_2 laser beam. By using a hot roller, slices are bonded to each other. Apart from the slice, unwanted material acts as support which is later removed. After completion of one slice the platform is lowered and by winding roll of material a fresh area of the sheet comes up. Upon completion of part sealing is done with epoxy resin, urethane lacquer or silicone fluid which prevent distortion via water absorption.

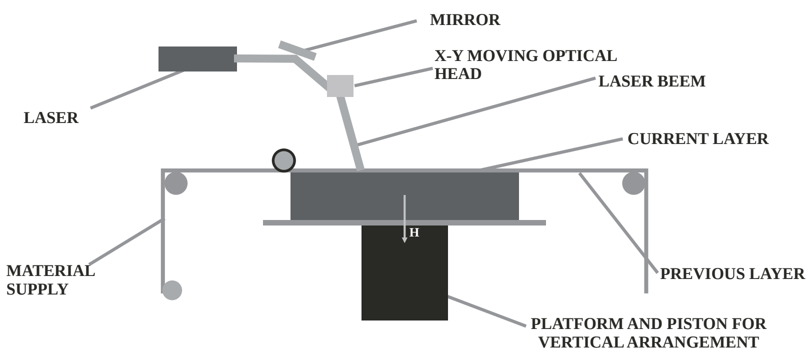

Figure 4: Schematic Diagram of Laminated Object Manufacturing

F) Build Mechanism

F.1 Raw material - Paper/Plastic sheets with adhesive on one side (solid).

F.2 Energy source - Laser is used to cut through the paper and an intermediate requirement for laser power.

F.3 Layer construction - Subtractive method to construct 2D section and the desired profile is cut from material sheet. Remaining portion is cut into small squares to facilitate its removal in a later state.

F.4 Condition of Completed Part - Parts built are buried in a stack of solid sheet which provides support for overhanging feature in a part.

G) Performance Characteristics

G.1 Dimensional Accuracy-0.4 mm gap, diameter 1 mm hole, gives best dimensional accuracy. Accuracy is in range +/- 0.005 inches.

G.2 Surface Finish- In this process additional process like grinding and polishing are required. In case of FF prototypes, surface finish along the z axis is rougher compared to that along the x-y axes, mainly due to stair stepping effect. Experimental result shows that orientation angles 15 to 45 degree gives sufficiently contrasting surface finish.

G.3 Build Time- Due to the grinding and polishing additional build time is required. Build time can be reduced by increasing the layer thickness but then the surface finish shall be compromised up to same extent. Changing the roller speed can also affect the build time of the part.

Fused Deposition Modelling

A) Company- Stratasys Inc. (founded by S. Scott Crump)

B) Year of manufacture-1990

C) Commercial models available- Dimension Elite, Fortus 250ms, Prodigy Plus, FDM quantum/maxum, Objet series, etc.

D) Working Principle-

In the FDM machine a movable head deposits molten material onto a substrate. The build material is heated just above its melting point such that solidification occurs in 0.1 seconds after extrusion. The important factors are material extrusion rate, nozzle speed, speed of head and support structure for overhanging parts. The latest FDM has two nozzles, one for support and other for part material.

E) Schematic diagram

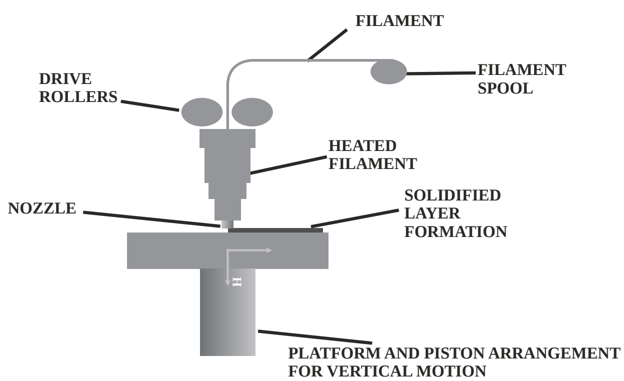

Figure 5: Schematic Diagram for Fused Deposition Modelling Apparatus

F) Build Mechanism

F.1 Raw Material - Thermoplastic material in the shape if filament (solid).

F.2 Energy Source - Solid material is melted by the heater present in the nozzle and then the molten material is solidified.

F.3 Layer Construction- 2D sections are constructed via material deposition.

F.4 Condition of Completed Part - Completed part is immersed in a fluid (air) that provides little support for the overhanging area or fluctuating components.

G) Performance Characteristics

G.1 Dimensional Accuracy- A negative air gap can decrease the accuracy.

G.2 Surface Finish- Due to the negative air gap the surface finish is degraded. Small beads increase surface quality.

G.3 Build Time- Smaller beads increase the built time.

Electron Beam Melting

A) Company - Arcam

B) Year – 1998

C) Commercial Model- Arcam S12, Arcam A2, Arcam Q10

D) Working Principle - In the first step, the part is designed in a 3D workspace. The model is then sliced into layers by the software. The electron beam is located on top of the vacuum chamber, is fixed and deflected to reach the entire area. The filament which is heated to a high temperature is emitting electrons, which are accelerated by an electric field. The electron beam is controlled by two magnetic fields whose function is to focus the beam and deflect beam to the desired point.

E) Schematic diagram

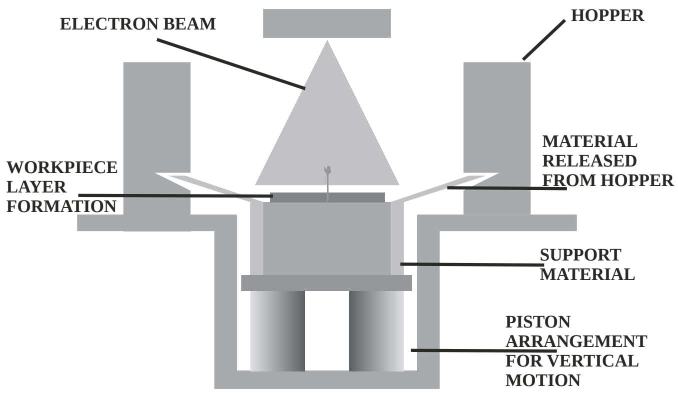

Figure 6: Schematic Diagram of Electron Beam Melting Apparatus

F. Build Mechanism

F.1 Raw Material - Fine Metallic Tool Steel, alloy steel, alloyed titanium, nickel and aluminum alloys.

F.2 Energy Source – Energy source of this process is electron beam which is controlled by two magnetic fields.

F.3 Layer Construction - The absorbed energy introduced as heat to the material (powdered form) leads to a phase transition from solid to liquid. After completion, the current layer is lowered down for the next layer generation.

F.4 Condition of Completed Part - Build Chamber is flooded with Helium gas to ensure proper cooling. Besides this, the component produced is subjected to heat treatment processes to achieve desired properties.

G. Performance Characteristics

G.1 Dimensional Accuracy - Parts dimensions up to 200 x 200 x 200 mm with dimensional accuracy of 0.4 mm can be developed.

G.2 Surface Finish -.One of the current drawbacks is the high surface roughness of parts which originates from relatively coarser powder feedstock. Finer powders beyond a limit tend to destabilize for vacuum system which is an essential requirement for EBM process (Mohammad *et al.*, 2014).

G.3 Build Time - Building speed is around 6 to 7 mm/hr. Deflection of beam is achieved without any moving parts leading to high Scanning speed.

Laser Engineered Net Shaping

A) Company-Sandia national laboratories, commercialized by CRADA participants-Optomec Design Company, MTS Systems, and AeroMet Corporation

B) Year of manufacture-1984

C) Commercial models available- L750, L850R

D) Working Principle - A high power laser melts metal powder due to the focus of the laser beam via a deposition head. The laser beam is focused on a small spot by one or two lenses and travels through the center of the head. Each layer is fabricated by moving the table in raster fashion. Upon completion of each layer the head is moved up. Metal powder is distributed by gravity or using a pressurized gas which is inert. This inert gas is used even in cases when not required for feeding as it typically shields the pool from oxygen, and provide better control of properties providing better surface wetting and adhesion of each layer to one another.

E) Schematic diagram

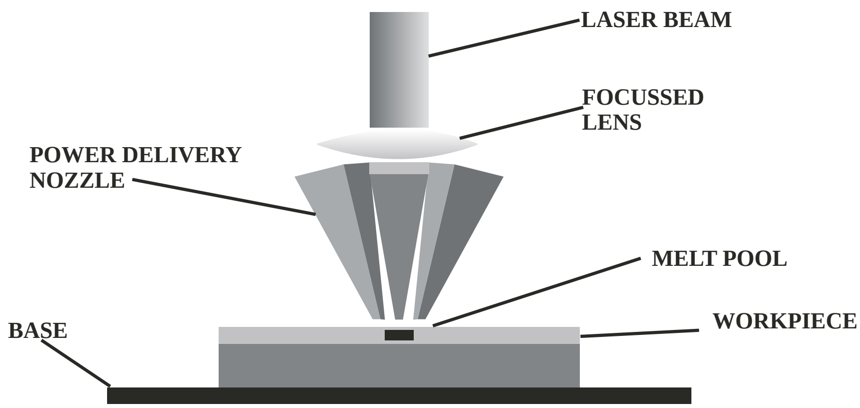

Figure 7: Schematic Diagram of LENS

F) Build Mechanism

F.1 Raw Material - Metallic powder with a shielded inert gas.(e.g.- Stainless Steel 316 alloy H13 Tool Steel, Titanium with 6% Aluminum and 4% Vanadium, Copper, Inconel)

F.2 Energy Source – Laser beam

F.3 Layer Construction - Powder is melted due to alignment of the focal point of the nozzle vs the laser, it can be mid-stream or while entering the pool, solidification of the molten metal occur due to relative movement, driven by the sliced 3D model, the heat dissipation takes place mainly from the substrate, a strong metallurgical bond is formed with the original surface. Thus a solidified deposit is formed due to the programmed tool path of each slice. The assembly of laser and nozzle ascends for forming the next layer in the vertical direction (Ivanova *et al.,* 2013).

F.4 Condition of Completed Part – In controlled argon atmosphere containing less than 10 ppm oxygen (Mudge *et al.,* 2007).

G) Performance Characteristics

G.1 Dimensional Accuracy - Technique gives low dimensional accuracy in the deposition plane- +/- .002

inches in the growth direction +/-.0.015 inches (Ensz *et al.*, 1998).

G.2 Surface finish - Poor surface finish is achieved which requires machining of the parts. In the direction perpendicular to deposition, a higher surface roughness is obtained. Along the scanning direction the surface profile is smoother. On extruded shape the surface finish is typically 250 micro inches (Keicher *et al.*, 1997).

G.3 Building time – Parameters on the low side are laser power of 400-500 W with a 1-mm spot size, deposition rates less than 1 in 0.3/hr and on the higher side are laser power of 2500-3000 W with a 3-4 mm spot size, deposition rates up to 14 in 0.3/hr (Mudge *et al.*, 2007).

Shape Deposition Manufacturing

A) Company - Stanford University's rapid prototyping laboratory

B) Year of manufacture – 1993

C) Commercial models available –Since this is an experimental process, machine exists only in two schools, Carnegie Mellon University and Stanford University (Blair *et al.*, 1999).

D) Working Principle - Here, the CAD model is converted to compact blocks. These are deposited as near-net shape using laser or plasma based deposition. Afterwards, every layer is accurately machined to shape using EDM or CNC milling. Residual stresses tend to develop which are controlled by shot-peening. After one layer, deposition of next layer takes place until the object is completed. Sacrificial support material is used to make supports in this case in which each layer is embedded (Merz *et al.*, 1994).

E) Schematic diagram

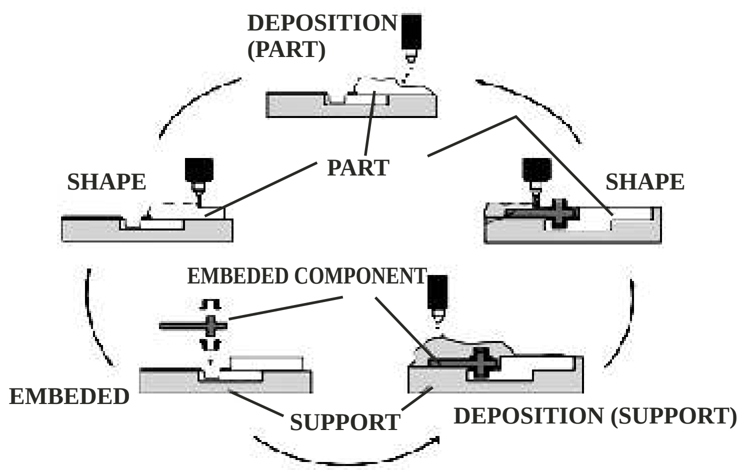

Figure 8: Schematic Diagram of Shape Deposition Modelling

E) Build Mechanism

E.1 Raw material- Metal in the form of powder is injected onto the substrate (e.g.-stainless steel, titanium, INVAR™, aluminum, bronze).

E.2 Energy source- 2.4 kW CW Nd: YAG laser source with a variable focal length

E.3 Layer construction- Fusion take place between injected powder and the substrate as the laser scans over the part, leaving a bead formation of deposited material. It is accurate as material is deposited only when laser strikes the surface, thus it is easy to selectively deposit material (Swami *et al.*, 1997).

E.4 Condition of completed part- This process involves stations where after metal deposition, metal removal, cleaning and stress relieving takes place. These stations are connected by a transfer robot. Therefore, the completed part is in ambient air.

F) Performance Characteristics

F.1 Dimensional Accuracy - ability to form very complex shapes with high dimensional accuracy.

F.2 Surface Finish - Can be improved by controlling and optimizing process variables. Obtained surface finish is better compared to only additive processes; however surface finish can be improved by using low shrinkage material. Residual stresses can lead to surface finish defects. Due to shrinkage a surface finish defect called Christmas tree effect takes place (Kietzman *et al.*, 1999).

F.3 Build time - Faster built time because of simultaneous curing of the entire layer, the number of layer can also be minimized to reduce the build time. The total time used for process preparation and finishing is 8 min, accounting for 19% of the total build time. Building time of the half-scale IMST2 test part is approximately 26 h. If two parts are built simultaneously the built time can be reduced by 25%.

Three Dimensional Printing

A) Company – Z Corp

B) Year of manufacturing- 1984

C) Commercial model – HD3DP, Z Printer 310 System, Z406 3D Printer, Z810 3D Printer.

D) Working Principle

The powder layers are applied to substrate. A nozzle sprays a binder which joins the layers. Mist of water droplets are employed so that the excessive disturbance due to binder hitting the layer is reduced. Upon completion of part it is heated; later the support is removed by immersion in a water bath. Then sintering is performed on the part. The powder grains and size of binder droplets determine the resolution (Pham *et al.*,1998).

E) Schematic diagram

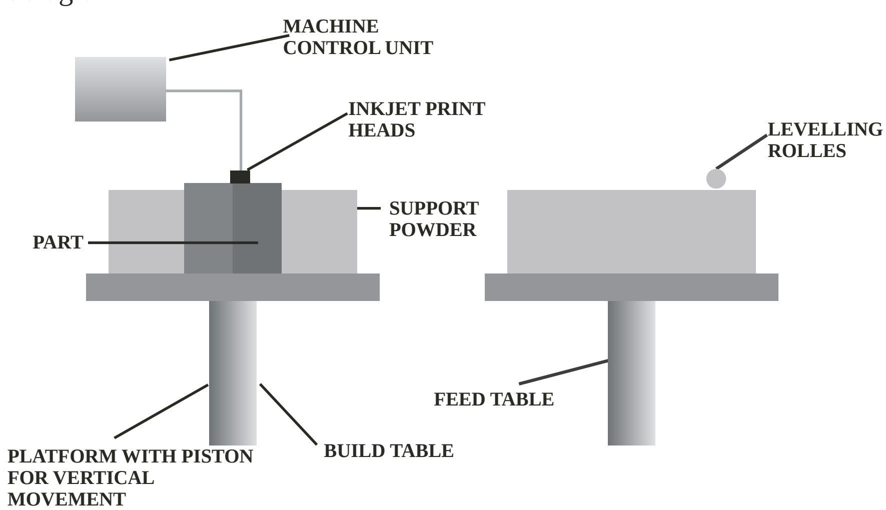

Figure 9: Schematic diagram of 3D printing

F) Build Mechanism

F.1 Raw Material - Acrylonitrile butadiene styrene (ABS) and Polylactic acid (PLA) are used as raw materials. The plastic comes as strands of filament that are usually a standard 1.75 millimeters or 3 millimeters in width along with wax like support structure. Acrylic powder and cyanoacrylate, ceramic powder and a liquid binder are used as a substitute.

F.2 Layer Construction - Molten plastic and wax are supplied to the jetting heads which releases tiny droplets of material and movement takes place in the working plane in a desired pattern to form a layer. Milling is done over the layer to maintain a uniform thickness.

F.3 Energy Source - Material hardening takes place due to the rapid dip in the temperature at the outlet of the head nozzle. The system requires material to be distributed accurately and evenly across the build platform. 3D Printers accomplish this task by using pressure energy of the roller mechanism.

F.4 Condition of Completed Part - Completed model is achieved by melting or dissolving the wax support.

G) Performance Characteristics

G.1 Dimensional Accuracy - Depends upon the Jet Headers which have a resolution up to

600 dots per inch and follow 'Drop on Demand' approach.

G.2 Surface Finish - Layer thickness about 0.004”, rate of layer formation – 1” to 2” per hour.

G.3 Build Time - Extremely efficient and fast in comparison to other GM techniques.

Ultrasonic Additive Manufacturing

A) Company- Solidica Inc. (founded by Dawn White)
B) Year of manufacture-2000
C) Commercial models available- Alpha Ultrasonic additive machine, etc.
D) Working Principle –

The computer program slices the model into horizontal cross section or layers from the 3D CAD model of the component to be built. An ultrasonic sonotrode which rotates and travels along length of metal foil applies a normal force. The sonotrode oscillates with 20 kHz frequency in direction of weld which results in generation of normal and oscillating shear forces. These stresses produce deformation to break the oxide film, producing clean surfaces. After deposition of a strip, another strip is deposited next to it. The process is repeated upon completion of a layer. Then, the layer is shaped into its sliced contours by a computer-controlled milling head. This can be done after either each layer or several layers. Upon shaping of the contour, chips are blown by compressed air and work for next layer continues.

E) Schematic diagram

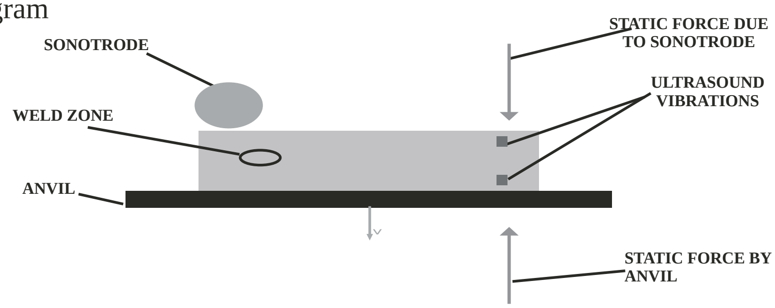

Figure 10: Schematic Diagram of Ultrasonic Additive Manufacturing

F) Build Mechanism

F.1 Raw material- Material comes in the form of flat sheets, tape segments, strands of filament or single dots of material. The material may be plastic or metallic, e.g. - strain-hardened 3003-H18, aerospace grade aluminum 2024, 6061 and 7075 etc.

F.2 Energy source- Low amplitude, high-frequency (typically 20,000 hertz) ultrasonic vibrations used along with high pressure (Kong *et al.*, 2004).

F.3 Layer construction- Layer construction occurs due to welding, plastic deformation and atomic diffusion. (Kong *et al.*, 2004).

F.4 Condition of completed part -laminated metal parts can be produced by welding foil layers continuously to previously deposited material; contour milling is used to create the profile of each layer. Completed part is in ambient air (Li *et al*., 2009).

G) Performance Characteristics

G.1 Dimensional accuracy-high dimensional accuracy because of additive and subtractive dimensional approach, unlike other additive processes here dimensional errors due to shrinkage, distortion and residual stresses are not significant.

G.2 Surface finish-Desirable surface finish is possible, although sonotrode-induced roughness is a major source of defects in ultrasonically consolidated parts. An intermediate machining step was included to minimize such defects. However improved sonotrode design may even eliminate need for machining. An EDM-modi? ed sonotrode had a good overlapping and an even surface texture (Yim *et al.*, 2012).

G.3 Build time- Welding speed here is directly influencing build time, low speed leads to better LWD but higher cost and built time, addition of machining process also increases the build time (Yim *et al.*, 2012).

Conclusion

The inferences drawn from the above detailed process comparative evaluation has been summed up in the two tables given below. Table 1 gives the Comparison of various RP technologies on the basis of Build mechanism. Table 2 gives the Comparison on basis of performance characteristics. These can basically be utilized for in-depth understanding of the process and thereupon for the process selection depending on the user's particular preferences.

Table 3: Comparison of various RP technologies on the basis of Build mechanism

	Comparison on the basis of build mechanism				
Technique	**Energy Source**	**Layer Construction**	**Condition of Completed parts**	**Support Material**	**Raw Material**
SLA	UV	Photo current solidification	Resin	Fluid	Photo polymer in liquid state
SLS	Laser	Sintering	Powder	Powder	Plastics and metal powder
LOM	Laser	Sticking of sheets	Paper	Solid sheet	Paper/ plastic sheet
FDM	Heater to form paste	Material Deposition	Air	air	Thermoplastic Material (ABS)
EBM	Electron Beam	Phase transition	Placed in cabin filled with Helium gas	Same as model material	Fine metallic tool steel, alloys
LENS	Laser	Spraying and solidification	Air	Beads of same material	Metallic powder (stainless steel 316 alloy)
SDM	Heater Paste	Bead Formation	Air	Waxes, Watersol --uble Polyacrylates	Powder (Stainless steel invar, aluminum, titanium)
3DP	Inkjet	Jetting	Model achieved by dissolving and melting the wax support	Molten plastic and wax	ABS, polylactic acid
UAM	Ultrasonic Vibration	Welding foil layer to previously deposited material	Ambient air	Preferably extrudable materials	Plastic or metallic sheet (Strain hardened 3003 –H18)

Table 4: Comparison on the basis of performance characteristics

Technique	Comparison on the basis of performance characteristics				
	Dimensional Accuracy	Surface finish	Build time	Process Strength	Weakness
SLA	± 0.005”	Very good	average	Sufficiently large component can be made accurately	Portability issues due to liquids, post processing problems
SLS	± 0.004” or 0.01’’	Good to very good	Average to good(0.6 t o 2.5 cm3/hr)	Variety in raw material, high accuracy	High cost, surface finish, weight and size
LOM	± 0.002”	Fair	120 sec	Cost ,size	Limited scope of material, surface finish and accuracy issues
FDM	± 0.005”	Fair	Poor(2.54 cm^3/hr)	Cost, material	Slow speed leading to large build time
EBM	0.016”	fair(light machining and griding is required)	Good to very good(3.7 $inch^3$/hr)/(45-66 mm^3 /s)	deliver mechanical strength with less mass, cost and weight is reduced, multipiece assembly as single component	High skill requirement, large power requirement
SGC	0.02”	Fair(finishing operation like sanding is needed)	Poor to good(100 layers/hour)	Does not require support structure(as wax fills the void),	Produces large waste, high operating cost, complex system
LENS	± 0.002”	As low as 8 micrometer is achievable under optimum condition	0.5 kg per hour/upto 60 mm^3/s	Combination of different material is possible, lowers cost and time requirement	Surface finish, secondary finishing proces s required, support structure problem
SDM	± 0.001”	Very good	Poor	Wide variety of material, use of conventional machine tools, no stair step effect unlike others, integrated complex structure can be made	High cost, support material require manual w ork for removal
3DP	0.004”	Fair	Very fast (25-50 mm^3/hr)	Build time, speed, cost effectiveness	Limited scope of material, surface finish, the parts produced are fragile in nature
UAM	± 0.015”	Good to very good*	77mm/sec Fast	Involves less he at so no melting hence no distortion, good bonding properties	Material has a tendency to shrink and develops brittle nature sometimes

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