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EXPERIMENT NO. 01

Aim: Study of Rapid Prototyping and Tooling.

Introduction: -

The term **Rapid Prototyping** (RP) refers to a class of technologies that can automatically construct physical models from Computer-Aided Design (CAD) data. The goal of Rapid Prototyping (RP) is to be able to quickly fabricate complex-shaped, three dimensional parts directly from CAD models.

Principle of Rapid Prototyping: -

The principal of RP is illustrated in fig.1(a). The CAD model of the object shown is sliced by parallel planes. The edges of the slices thus obtained are squared. Thus, a complex 3D object is decomposed into several 2D objects or slices. In other words, a complex 3D manufacturing problem is converted into several simple 2D manufacturing problems. These slices are physically realized in one of several ways, stacked and pasted together as shown in fig, to obtain the physical prototype. The accuracy of these prototypes, due to the staircase effect, can be improved by decreasing the slice thickness. For even better finish, polishing can be applied.

![Figure 1: Principal of Rapid Prototyping](image)
Each physical layer will be placed over the previous one. If the previous layer is smaller than the current one, then it will not be able to fully support the current layer. For this purpose, a complementary shaped sacrificial layer of a different material is deposited and fused to the previous layer using one of several available deposition and fusion technologies. The sacrificial material has two primary roles: first, it holds the part, analogous to a fixture in traditional fabrication techniques; second, it serves as a substrate upon which unconnected regions and overhanging features can be deposited. The unconnected regions require this support since they are not joined with the main body until subsequent layer are deposited. Another use of sacrificial material is to form blind cavities in the part. The collection of this sacrificial layer is called support structures.

Rapid Prototyping Process Step: -

Although several rapid prototyping techniques exist, all employ the same basic five-step process. The steps are:

1. Create a CAD model of the design
2. Convert the CAD model to STL format
3. Slice the STL file into thin cross-sectional layers
4. Construct the model one layer atop another
5. Clean and finish the model

RAPID TOOLING: -

A much-anticipated application of rapid prototyping is rapid tooling, the automatic fabrication of production quality machine tools. Tooling is one of the slowest and most expensive steps in the manufacturing process, because of the extremely high quality required. Tools often have a complex geometry, yet must be dimensionally accurate to within a hundredth of a millimeter. In addition, tools must be hard, wear-resistant, and have very low surface roughness (about 0.5 micrometers root mean square). To meet these requirements, molds and dies are traditionally made by CNC-machining, electro-discharge machining, or by hand. All are expensive and time consuming, so manufacturers would like to incorporate rapid prototyping techniques to speed the process. Peter Hilton, president of Technology Strategy Consulting in Concord, MA, believes that "tooling costs and development times can be reduced by 75 percent or more" by using rapid tooling and related technologies.

Types of Rapid Prototyping: -

(i) Indirect Tooling: -

Most rapid tooling today is indirect: RP parts are used as patterns for making molds and dies. RP models can be indirectly used in a number of manufacturing processes:

- Vacuum Casting: In the simplest and oldest rapid tooling technique, a RP positive pattern is suspended in a vat of liquid silicone or room temperature vulcanizing (RTV) rubber. When the rubber hardens, it is cut into two halves and the RP pattern is removed. The
resulting rubber mold can be used to cast up to 20 polyurethane replicas of the original RP pattern.

A more useful variant, known as the Keltool powder metal sintering process, uses the rubber molds to produce metal tools. Developed by 3M and now owned by 3D Systems, the Keltool process involves filling the rubber molds with powdered tool steel and epoxy binder. When the binder cures, the "green" metal tool is removed from the rubber mold and then sintered. At this stage the metal is only 70% dense, so it is infiltrated with copper to bring it close to its theoretical maximum density. The tools have fairly good accuracy, but are limited to less than 25 centimeters in size.

- Sand Casting: A RP model is used as the positive pattern around which the sand mold is built. LOM models, which resemble the wooden models traditionally used for this purpose, are often used. If sealed and finished, a LOM pattern can produce about 100 sand molds.

- Investment Casting: Some RP prototypes can be used as investment casting patterns. The pattern must not expand when heated, or it will crack the ceramic shell during autoclaving. Both Stratasys and Cubital make investment casting wax for their machines. Paper LOM prototypes may also be used, as they are dimensionally stable with temperature. The paper shells burn out, leaving some ash to be removed.

To counter thermal expansion in stereo lithography parts, 3D Systems introduced Quick Cast, a build style featuring a solid outer skin and mostly hollow inner structure. The part collapses inward when heated. Likewise, DTM sells True form polymer, a porous substance that expands little with temperature rise, for use in its SLS machines.

- Injection molding: CEMCOM Research Associates, Inc. has developed the NCC Tooling System to make metal/ceramic composite molds for the injection molding of plastics. First, a stereo lithography machine is used to make a match-plate positive pattern of the desired molding. To form the mold, the SLA pattern is plated with nickel, which is then reinforced with a stiff ceramic material. The two mold halves are separated to remove the pattern, leaving a matched die set that can produce tens of thousands of injection moldings.

(ii) Direct Tooling:

To directly make hard tooling from CAD data is the Holy Grail of rapid tooling. Realization of this objective is still several years away, but some strong strides are being made:

- RapidTool: A DTM process that selectively sinters polymer-coated steel pellets together to produce a metal mold. The mold is then placed in a furnace where the polymer binder is burned off and the part is infiltrated with copper (as in the Keltool process). The resulting mold can produce up to 50,000 injection moldings.

In 1996 Rubbermaid produced 30,000 plastic desk organizers from a SLS-built mold. This was the first widely sold consumer product to be produced from direct rapid tooling. Extrude Hone, in Irwin PA, will soon sell a machine, based on MIT’s 3D Printing process, which produces bronze-infiltrated PM tools and products.
• Laser-Engineered Net Shaping (LENS) is a process being developed at Sandia National Laboratories and Stanford University that will create metal tools from CAD data. Materials include 316 stainless steel, Inconel 625, H13 tool steel, tungsten, and titanium carbide cermets. A laser beam melts the top layer of the part in areas where material is to be added. Powder metal is injected into the molten pool, which then solidifies. Layer after layer is added until the part is complete. Unlike traditional powder metal processing, LENS produces fully dense parts, since the metal is melted, not merely sintered. The resulting parts have exceptional mechanical properties, but the process currently works only for parts with simple, uniform cross sections. Commercialization is still several years away.

• Direct AIM (ACES Injection Molding): A technique from 3D Systems in which stereolithography-produced cores are used with traditional metal molds for injection molding of high and low density polyethylene, polystyrene, polypropylene and ABS plastic. Very good accuracy is achieved for fewer than 200 moldings. Long cycle times (~ five minutes) are required to allow the molding to cool enough that it will not stick to the SLA core.

In another variation, cores are made from thin SLA shells filled with epoxy and aluminum shot. Aluminum’s high conductivity helps the molding cool faster, thus shortening cycle time. The outer surface can also be plated with metal to improve wear resistance. Production runs of 1000-5000 moldings are envisioned to make the process economically viable.

• LOM Composite: Helysis and the University of Dayton are working to develop ceramic composite materials for Laminated Object Manufacturing. LOM Composite parts would be very strong and durable, and could be used as tooling in a variety of manufacturing processes.

• Sand Molding: At least two RP techniques can construct sand molds directly from CAD data. DTM sells sand-like material that can be sintered into molds, while Soligen 3D Printing machines can produce ceramic molds as well.
EXPERIMENT NO. 02


INTRODUCTION

The demand for shorter development time, time-to-market and reduced product life cycle resulted for the emergence of a new paradigm called Rapid Prototyping (RP) or Layered Manufacturing (LM) process. The success of automotive, electronics, telecommunications, biomedical, packaging appliances, leisure and sports industries in responding to rapidly varying customers demand for higher quality standards with lower costs depend on the ability to develop the product with the application of state-of-art technology.

Layered Manufacturing introduced in late 80’s as a design visualization tool, has revolutionized the way products are designed and manufactured today. Although the prototypes could be made out of only soft material, very soon, innovative methods of making the short-run and production tools were developed, called as Direct Rapid Tooling Processes.

Selective Laser Sintering (SLS) is the commercially successful metallic RP process so far. Direct Metal Sintering relies on laser induced melting of powder particles together. Since significant thermal gradient exist using this route, the powder bed temperatures are controlled to a value just below the powder melt temperature to produce parts with minimum internal stresses. Porosity is a problem that is normally reduced by post sintering or infiltration.

The principles of Laminated Object Manufacturing (LOM) another commercially successful RP process for making paper based prototypes, have been used for making metallic laminated tools and parts. The metallic laminates in this method are bolted together rather than gluing or brazing, thus it lacks the complete adhesion between layers. This method is not suitable for processes such as injection molding where liquid metal is involved. Furthermore, this LOM process suffers from high material wastage and inherent inability to have adaptive layer thickness.

Various droplet production processes thermal spraying, micro-casting and welding have been developed for making metallic objects and tools to improve the deposition quality and to attain the desired contour profile shape. Comparatively three-dimensional welding has the
ability to produce strong, fully homogeneous dense metal parts in layers [8]. Adaptation of a weld cladding technique has enabled the production of parts wider than normally possible from single weld beads. But attaining the required surface finish and required contour profile is difficult with the weld deposition [9]. So, to attain better dimensional accuracy and surface quality for building metallic dies and molds it was proposed to develop a unique methodology with a hybrid approach of an additive and subtractive processes comprising MIG-MAG welding and CNC machining respectively.

HYBRID LAYERED MANUFACTURING

The proposed Hybrid Layered Manufacturing (HLM) process has a numerical controlled system that integrates the synergic MIG-MAG welding process, which provides the controlled heat and mass transfer with precise depth of bead penetration, and CNC milling process, which enhances both the surface quality and dimensional accuracy with great manufacturing agility. Synchronization of welding process and work-piece/substrate motion with milling operation offer a new accelerator way of building desired metal parts and tools.

The aim and scope of the proposed process is

- To develop a RP machine for making injection molds and dies.
- To develop the know-how to retrofit any exiting CNC machining center with the above RP capability.
- To develop the software required for this HLM process that does

Slicing process
- Path generation to control welding torch and milling cutters
- Generation of codes to control process parameters such as spark initiation,
- Control the speed and feed of the milling cutter
- Post-processing to make the code suitable for the controller of any CNC m/c.

The HLM process consists of a software program which uses the zeroth order edge approximation uniform slicing strategy of the RP paradigm to calculate each slice thickness that to be deposited with the required filler metal as successive layers from lower to topmost layer with the welding process. Further in accordance to the first order edge approximation slicing strategy of RP it generates the required CNC code for machining of the deposited metallic layers from top to bottom layer direction to attain the required contour profile shape with user specified accuracy.
Slicing Strategies

Fabrication of the prototype model through RP process requires the thickness of each layer to be found before deposition of the material. To calculate the Slice Thickness, i.e. the distance between the top profile contour and bottom profile contour of a specific layer.

Based on the layer thickness, the slicing strategies can be broadly grouped into two.

- **Uniform Slicing** where the layer thickness is same for all layers of the object
- **Adaptive Slicing** where the thickness of each layer is dependent on the local geometric properties and the user specified cusp height.

Slicing schemes can be classified based on the edge approximation that is how each bottom and top contour relates to respect to the build direction

- **Zeroth Order Edge Approximation**: The edges of the layers are along the build direction. The boundary of the final part will be a stepped approximation of the CAD model.
- **First Order Edge Approximation**: The slice thickness has been formed by a curve of first order i.e. a straight line. This is also referred to as ruled slicing.
- **Higher Order edge approximation**.

The stereo lithography (STL) file of the body is sliced at regular intervals with the consideration of Flat Surfaces, Peak Points and Branching constraints to form the *Coarse Slices* and then further to have *Fine Slices* as shown in Figure 1 and Figure 2.
In a *Coarse Slicing*, the number of loops in the top \(z\)-level and that in the bottom \(z\)-level will be the same i.e., for each loop in the bottom \(z\)-level there will be a corresponding loop at the top level. In this slicing process it is essential to establish the mapping between the top and bottom contours of a coarse slice.

In *Fine Slicing*, each individual coarse slice is further sub-divided in accordance to the user defined/required uniform slice or adaptive slice thickness.

Though the above slicing procedure for the STL file takes more computational time, the results will be more accurate with the simplification of the geometry of the complex CAD model. The first step i.e., Coarse Slicing is helpful in establishing contour mapping and in eliminating branching constraint. The second step, Fine Slicing is an iterative process to calculate slice thickness based on the local curvature of the body. The data attained through the Fine Slices is utilized for the path generation of the MIG-MAG welding gun, and face milling operation.

**METHODOLOGY FOR LM**

The proposed HLM process consists of the following stages:

- Building a near-net shape of the tool.
- Rough Machining the near-net shape of the tool to final dimensions
- Heat treatment for stress relieving and strengthening
- Finish Milling to get the required surface finish and quality.

**Building the near-net shape of the tool**

The substrate plate is rigidly placed with proper fixtures on the XY table, and its motion is guided by motor drives. The required weld paths are generated in relation to the *Fine Slice contours* for deposition of the layer thickness is used to deposit the bottom most layer with a simple zigzag pattern. As the metal deposition in the bottom most layer is completed the shielding gas nozzle is turned off and the switching functions are invoked to change over between welding and face milling process by halting the welding process and activating the face milling process and vice versa. For this operation a pneumatic system is used to swivel between welding gun and the milling cutter. So that at any time either welding or milling operation will
only take place. The necessary functions for the operation of synergic MIG-MAG welding machine with shielding gas were monitored through the numerical controller. While the majority of the welding process parameters such as current, voltage, arc gap, shielding gas composition etc are controlled externally.

**Rough machining the near-net shape of the tool to final dimensions**

Face milling operation is performed on the top surface of each deposited metal layer to get the required thickness of the layer. The instability of arc welding process may cause a malfunction/defect in the middle of the weld bead. To minimize the deviation and correct the vertical height accuracy of the built layer in successive multiple layer deposition, face milling operation is performed on all the horizontal surfaces of the deposited layer. Repeating the above process of layer deposition and face milling operations to generate near net layers deposited one over the other from bottom most to top layer till a casting like rough shape is obtained.

As the size of the deposited layer is made to be little bit larger than the actual required profile shape considering into account the shrinkage and weld defects, the edges of the layers are still rough. The tool path of the end mill is generated for machining the final casting like rough shape from top to bottom layer direction of the deposited metallic layers to attain the required contour profile shape with user specified accuracy in accordance to first order edge approximation strategy slicing principle of RP paradigm.

**Heat treatment for stress relieving and strengthening**

The temperature gradients within the deposited layer with the severity of cooling, influences on the generation of internal stresses and on the resulting microstructure of the final deposited layer. The stress distribution consists of nearly uniform tension in the newly deposited layer, with tension at the top of the substrate and nearly uniform compression at the bottom half of the substrate. To relieve these undesirable residual stresses, a suitable heat treatment is performed using normalizing and annealing processes. As these residual stresses are unchecked, they may induce warping, loss of edge tolerance and delaminating thereby reducing the strength and influencing on the tool life.

The material homogeneity of the prototype to be obtained in the proposed method is between those of cast and machined parts. Thus, this process is not suitable for making forging dies where very high impact forces are encountered. The die used in injection molding, die casting and sheet metal forming undergo considerably less fatigue loading during the operation, so these tools can serve the purpose even without any homogenization operation such as Hot Isostatic Pressing (HIP ping) process. Further these die halves are free from overhanging features, as they need to open and close in operation. Building such dies and mold with free from re-entrant profiles by
the proposed methodology will not require support structure, thus making the process less complicated.

**Finish machining**

Finish mill all the contour profiles of the tool to the required surface finish.

**Process of LM**

A step-by-step processing of a sample model is described in this below section. All the subsequent sequence of operations is carried out on it to generate the weld deposition paths and the coarse slice machining paths.

**Input Model**

Using the Pro/E CAD package, a solid model bracket without any overhang features is drawn as shown in Figure 4 and its STL output file is generated. This .STL file acts as an input for the software. Then the user defines the process parameters required for the further subsequent sequence of operations to be carried out on it to generate the weld deposition paths and the coarse slice machining paths.

**Coarse Slice Model**

Next the .stl model is coarse sliced to generate the coarse slice levels as shown in Figure 5. This is followed by generation of the solid coarse slices and their display.

![Fig.4 Model dimensions](image1.png)  ![Fig.5 Coarse slices display](image2.png)

**Uniform Slice Model**

The model is uniformly sliced in accordance to the user-defined settings and the uniform layers are generated to display as shown in Figure 6.
Weld Path

The area-filled weld paths along with the face mill paths are generated and can be viewed as in Fig.7

Milling Paths

The .stl model is fed for the machining path generation. The paths thus generated along with the tool withdrawal and reentry points can be viewed in Figure 8

Output Files

The output files generated from the software i.e., the weld deposition path, face mill cutter path and the coarse slice-machining path are of standard NC format. These output files are fed to the NC drive controller to generate the milling and deposition paths.
Advantages of LMT

The list is not very long; however, the advantages listed are very important indeed, giving LMT technology a distinct place in the field.

- **Design freedom.**  
  Using LMT the design freedom is almost unlimited. Even hollow prototypes and functioning assemblies can be produced in one run. CNC milling is at a disadvantage too for sharp inner corners. As tools are by definition round, many sharp inner corners cannot be machined.

- **Complex geometry is just as easy**  
  The price of an LMT prototype is independent of its complexity. For CNC machining dependence is present: in the case of many details a small tool has to be used with a small tool path distance, resulting in a long production time.

- **Ease of use**  
  In theory LMT systems have the advantage at this point, as there is no need to first make a block of material in the correct dimensions and then fix it on to the machines working table. In practice most LM machines are not yet so easy to use. A large number of process parameters have to be correctly set: it may take up to a few months before a new machine is actually operating. For most LMT processes some (laborious) manual post processing is needed as well. The new generation of Concept Modelers using '3D printing' technology achieves much better, promising real black-box 3D printers for the near future.

**However, there are disadvantages also of LMT**

- There are limited material options. These materials are proprietary and hence costly.
- Finish is nowhere close to machined surface.
- Poor dimensional accuracy and stability.
- Anisotropy.
Experiment No - 03

Aim: Study of Laminated Object Manufacturing (LOM).

Laminated Object Manufacturing

In this technique, developed by Helisys of Torrance, CA, layers of adhesive-coated sheet material are bonded together to form a prototype. The original material consists of paper laminated with heat-activated glue and rolled up on spools. As shown in the figure below, a feeder/collector mechanism advances the sheet over the build platform, where a base has been constructed from paper and double-sided foam tape. Next, a heated roller applies pressure to bond the paper to the base. A focused laser cuts the outline of the first layer into the paper and then cross-hatches the excess area (the negative space in the prototype). Cross-hatching breaks up the extra material, making it easier to remove during post-processing. During the build, the excess material provides excellent support for overhangs and thin-walled sections. After the first layer is cut, the platform lowers out of the way and fresh material is advanced. The platform rises to slightly below the previous height, the roller bonds the second layer to the first, and the laser cuts the second layer. This process is repeated as needed to build the part, which will have a wood-like texture. Because the models are made of paper, they must be sealed and finished with paint or varnish to prevent moisture damage.

Figure: Schematic diagram of laminated object manufacturing.
Helisys developed several new sheet materials, including plastic, water-repellent paper, and ceramic and metal powder tapes. The powder tapes produce a "green" part that must be sintered for maximum strength. As of 2001, Helisys is no longer in business.

**Advantages**

- Only the outline is cut and no time is spent in building the interior of the layer. Therefore, this process is fairly faster.
- The materials used for building the parts are the least expensive among all RP processes.
- Cost of the machine is one of the lowest.
- No external support structures or post-curing is required.
- It is suitable and economical for making large parts to be used as patterns for sand castings.
- The process can be carried out unattended.
- LOM is also a direct Rapid Tooling process. It has been successfully used in making metallic laminated tools for sheet metal forming operations.

**Limitations**

- Parts are weak along Z-direction.
- Paper parts have poor surface finish and absorb moisture.
- The process is not suitable for making small intricate parts. As the stock needs to be chipped out during decubing, it requires a fair amount of skill is required.
- There is a lot of material wastage.
Aim – To study about selective laser sintering.

Selective laser sintering process was originally developed at the university of Texas at Austin in USA and then commercialized by DTM corporation, USA. It was subsequently developed and marketed EoS, Germany also. In SLS a layer of powdered material is spread out and levelled over the top surface of the growing structure shown in fig. A laser then selectively scan the layer to fuse those area defined by the geometry of the cross section. The laser energy is also fuses layers together. The unfused material remains in place as the support structure. After each layer is deposited the platform lowers the part by the thickness of the layer is deposited, the platform lowers the part by the thickness of the layer, and the next layer of powder is deposited. When the shape is completely built up, the part is separated from the loose supporting powder. Several type of materials are in use including plastics, waxes and low melting temperature metal alloy.

This process has been successfully proved for making steel die insert for short run production. For making steel dies on DTM’s SLS machine, the raw material is steel powder with each steel particle coated with polymer that act as binder. The same machine is used for non-metal as well as steel prototypes. When the building takes places, only the binder coating is fused keeping the particles together. Thus what is obtained at the end is green part. This green part is put in the
special oven to complete the sintering when the binder evaporates leaving it a porous part. Subsequently it is put inside another chamber for several hours to impregnate the pours with copper. Copper impregnation is required both to get dense parts as well as good polishability. In Eos’s SLS process, there is one machine for each material. Viz, EOSINT-P for polymer, EOSINT-C for ceramic and EOSINT-M foe metallic process prototypes. There is no binder coating on the metallic particle and the metallic powder is not strong steel but one with lower melting point. The laser used for making metallic part is sufficiently powerfull to fuse the metallic particles. The metallic particle in EoS process apparently do not require post-sintering as well as copper impregnation. However, its laser is more powerful. For making ceramic molds. The sand particles are coated with a binder as is done for steel tool in the case of DTM’s SLS process.

**Advantages**

1. Any material that can be converted in to powders and can be bonded together by fusing its particles at a reasonably low temp. can be used for making the parts in SLS process. Material commonly used for making parts in this process are nylon, ABS and investment casting wax.
2. This is the commercially available direct RP process to make prototypes out of the metals. Hence this is useful for tool makers.
3. This can also produces ceramic mold cavities directly and hence there is no need for patterns.
4. Parts obtained are tough.
5. No external support structure are required.
6. No post curing is required for non metals. Only metal parts required sintering.
7. There is no wastage of material.

**Disadvantage**

1. This is one of the costly process.
2. Surface finish of part is grainy.
3. Parts are porous in nature.
4. The building operation needs to be monitored.
(5) Long time is required to heat up the material chamber before building the parts and to cool it down after the building is over.
Experiment No – 05

Aim - Study of Shape Deposition Manufacturing

Process Description

Shape Deposition Manufacturing (SDM) is a patented rapid prototyping process developed at Carnegie Mellon University in the early 1990’s. The SDM process involves material deposition followed by shaping to create geometry in three dimensions. Separate part and support materials are used in SDM. The support material is used to support undercut features and is etched away after a part is completed. The overall process is illustrated in figure 1.

![Figure 1](image1)

The construction of a single layer of a more complex part (a sphere inside a box) is shown in Figure given below.

![Figure 2](image2)
SDM parts are made by a combination of direct shaping of part material and replication of support material features into part material. If a surface is visible from the build direction, then it can be directly shaped into the desired geometry. This process is shown in Sequence A of Figure 3.

If the part material features in question are undercut or face away from the build direction, then these features will be constructed indirectly. First, support material will be directly shaped into the negatives of the features; this support material will serve as a mold. Then, part material will be deposited over these negatives, replicating their geometries and forming the desired positive features. This indirect construction method is shown in Sequence B of Figure 3. "Combination" features which have both undercut and non-undercut faces are built using a combination of these methods. This combined technique is illustrated in Sequence C of Figure 3.

The SDM process begins with the construction of a support material cavity shaped like the underside of the bottom of the desired object. Part material is deposited into this cavity; this will be the bottom layer of the object. If necessary, additional upward-facing features are milled into the exposed part material. Additional support material is deposited to surround the bottom layer.
of part material. If there are any undercut features in the second layer of the part, then additional support material will be deposited and shaped to support them. Part material is deposited to construct the second layer of the part. It is machined into the proper geometry and then surrounded by support material. This process is cyclically repeated until all layers of the part have been built. At this point, the whole object has been constructed, but it is embedded in a block of support material. To complete the process, the sacrificial support material is removed, leaving the finished part.

**Part Decomposition and Planning**

The process of planning a part's construction sequence in Shape Deposition Manufacturing is divided into two steps. First, the part is decomposed into manufacturable "compacts" - segments of a single material which have no undercut surfaces. Second, the material deposition paths and cutting tool paths required to make the sequence of compacts are generated.

The decomposition step requires a computer solid model of the part to be made. The model is subtracted from a block of solid material to produce a model of the complementary support material required to construct the part. The part and support models are then searched for the locations of "silhouette loops," paths which divide a solid into undercut and non-undercut regions. The separate models are completely subdivided into no undercut compacts. This planning operation is shown in Figure 4. For most reasonable part, these compacts can be ordered in a manufacturable sequence. Such a sequence requires that for any given compact, all compacts which support it can be built previously.
Pathological parts may have groups of compacts with cyclic dependencies, preventing such a sequence from existing. In this case, some of the compacts must be further divided to produce a manufacturable sequence. These decomposition steps require various tools available in solid modeling geometry engines. The original SDM planner used the NOODLES solid modeling system, developed at CMU. Later planners used the ACIS solid modeling kernel, available commercially. Current efforts include porting the current planner to run within the Unigraphics CAD/CAM system.

**Decomposition into Manufacturable Compacts**

After a manufacturable sequence of compacts has been generated, the machine instructions for generating each compact must be determined. This requires the creation of both deposition paths and toolpaths for the material shaping system. Early SDM planners used an offsetting strategy to generate both deposition paths and cutter toolpaths from the outlines of compacts. Later research has centered around the use of an algorithm called the Medial-Axis Transform to make space-filling deposition paths which are optimized for the material deposition systems involved.

**Hardware**

Several systems are required to build parts via Shape Deposition Manufacturing. Part material and support material deposition systems, a material shaping system, and a materials handling system are all required by this process.

Material deposition systems vary greatly according to the materials in question. Metallic materials have been deposited by several systems. The original metal deposition system used at Carnegie Mellon University was the "micro caster." A micro caster is a patented device which feeds material in wire form into an arc, where it is melted and allowed to fall as droplets. Another material deposition system used for metals is a laser combined with a powder feeder. The laser creates a melt-pool on a substrate; the powder feeder deposits powders into this melt pool for deposition onto the substrate. A combination of powder feeders with different materials can be used to make multimaterial or functionally graded materials; this process can also be used for ceramic powders. More recent material deposition techniques have included sputtering and etching, to make thin features for embedded sensors. Polymeric materials, the focus of the
remainder of this thesis, are extruded or cast using deposition systems which vary according to the exact material involved.

The original materials shaping system for Shape Deposition Manufacturing was a computer-controlled 3-axis vertical milling machine. A later implementation of the process used a five-axis milling machine for the creation of more general geometries. Metallic parts have also been shaped using electrical-discharge machining. Since the Shape Deposition Manufacturing process requires cyclic material deposition and shaping to make a part, all of these activities must occur in a common, repeatable reference frame. This can be accomplished by performing all of these processes on a single machine or else ensuring repeatable placement on the different machines involved. Pallet systems with repeatable positioning systems have been used by the SDM systems at Carnegie Mellon University and Stanford University. Parts are built on metal pallets which attach to pallet receivers mounted on all deposition and shaping machines. This palletizing system has the additional advantage of allowing parts to be removed from machines unless they are being actively manipulated. That is, if parts are cooling or otherwise waiting between process steps, they can be pulled from machines to allow other parts to be processed.

Material handling for Shape Deposition Manufacturing can be manual or automated. In the CMU and Stanford systems, robots can be used to transfer pallets between individual machines. The CMU robot is a rotary system placed in the center of a group of machines, while the Stanford robot is placed on a linear track which allows it to move between machines arrayed in a line.

**Comparison to Other Rapid Prototyping Processes**

Compared to most other rapid prototyping techniques, SDM has the advantage of decoupling material properties from deposition characteristics. This decoupling occurs because part features are created in SDM through material addition and removal rather than material deposition alone. Processes such as Stereolithography, Selective Laser Sintering, Fused Deposition Modeling, and Three-Dimensional Printing are purely additive; material must be deposited in the desired final or "net" shape. This requires compromises between materials with optimal properties and materials which can be deposited to net shape. SDM allows materials to be optimized for excellent final-part properties, without regard to whether they can be deposited to net-shape. This is possible because the final geometry will be machined into the part material, or replicated from
machined support material. As a result, a broader range of materials can be processed using SDM than is possible through purely additive rapid prototyping techniques.

While most rapid prototyping processes involve only material deposition, there are some processes that involve depositing and shaping material on a layer by layer basis. Laminated Object Manufacturing adds additional paper layers to a part and then outlines the periphery of those layers using a laser. The Solid Ground Curing process involves planning a layer of part and support material to an exact thickness. The Sanders process works the same way although a unique style of milling cutter is used. These processes first deposit an entire planar layer of material and then outline or plane that layer. Either one or two dimensions of geometrical information in such processes is completely determined by the material deposition process involved. In contrast to these processes, Shape Deposition Manufacturing uses the successive deposition and shaping of a series of "compacts" to produce a part. Several compacts, each with fully three-dimensional shapes, generally compose a layer of an SDM part. These SDM layers need not have a constant thickness or even be planar at all. SDM can deposit and shape geometries which are purely three dimensional, in contrast to the 2-1/2-dimensional stacked layers produced by the other more limited additive and subtractive processes.

All of the commercially available rapid prototyping processes manufacture parts from a series of planar layers; these layers are usually the same thickness throughout a part. This use of planar layers produces stairsteps on any slanted surfaces of the resulting parts. This is undesirable because of the resulting reduced part accuracy and poor surface finish. If a smooth slanted surface is desired, the part can be reoriented so that this surface will be vertical or horizontal while the part is built. If multiple smooth surfaces are desired, such a reorientation is generally impossible, and manual postprocessing such as sanding is required. Such handwork produces smooth surfaces, but at the cost of whatever geometrical accuracy is achievable by a machine. Since SDM compact shapes can be defined by three or five-axis milling, slanted surfaces can be accurately built without stairsteps.

Besides Shape Deposition Manufacturing, there are two other rapid prototyping processes which can produce parts with fully three-dimensional features: Controlled Metal Buildup and Multiple Material Machining. Controlled Metal Buildup is a technique being developed by the Fraunhofer Institute of Production Technology. This process uses laser deposition of metal powders to build parts. Three-axis milling defines the outlines and top surfaces of each layer.
Researchers plan to use five-axis machining to produce smooth oblique sides on parts. This process is the very similar to Shape Deposition Manufacturing although support materials have not been used with the technique, limiting the possible part geometries. Multiple Material Machining is also very similar to SDM; separate part and support materials are used (although they are named differently), and features are created via machining and replication from support material. While the use of milling to define geometry allows the creation of fully three-dimensional features in SDM, using milling cutters for shaping does place some limits on producible features. If a square pocket into part material is desired, rounded interior corners will generally, be produced by the milling cutters used.

One of the advantages of Shape Deposition Manufacturing compared to most other rapid prototyping techniques is the ease with which heterogeneous structures can be manufactured. Multi material parts and parts with embedded objects are both relatively easy to construct because of the modularity of the process sequence. Since there are frequent breaks between material deposition and shaping steps, the process can be interrupted often, and part materials changed or objects inserted. Changing part materials is as simple as switching between material dispensers in a single machine or moving a pre-referenced pallet from one machine to another. Embedding objects is as simple as laying objects into cavities between one machining step and the next deposition step. In most other processes, this is much more difficult.

Most rapid prototyping processes are designed to operate with a very limited set of materials, some of which may even be incompatible with one another. Changing part materials in a machine can be relatively easy or quite tedious. An example of an easy task is replacing the spool of filament on an FDM machine. A challenging task is changing an entire vat of SLA resin and cleaning the whole machine before introducing an incompatible resin. In some processes, changing materials within a part might require purging one-part material, inserting another, and resetting software parameters. In other processes, instant changes in material may be impossible. Changing materials in the Selective Laser Sintering process would probably lead to blended material parts, if the environmental and laser parameters for one material didn't damage or destroy the other material involved. These examples illustrate that using different materials within a single part is often more difficult in other processes than in SDM.

In conclusion, multi material parts and parts with embedded objects can be built more easily through Shape Deposition Manufacturing than through most other rapid prototyping systems.
This is a principal advantage of the process, and allows the production of parts which could be made only with great difficulty through other methods.
Experiment no –06

Aim: Study and demonstration of 3D printing

Introduction

3D printing is a form of additive manufacturing technology where a three dimensional object is created by laying down successive layers of material. 3D printers are generally faster, more affordable and easier to use than other additive manufacturing technologies. 3D printers offer product developers the ability to print parts and assemblies made of several materials with different mechanical and physical properties in a single build process. Advanced 3D printing technologies yield models that closely emulate the look, feel and functionality of product prototypes. A 3D printer works by taking a 3D computer file and using and making a series of cross-sectional slices. Each slice is then printed one on top of the other to create the 3D objects.

Background

One method of 3D printing consists of an inkjet printing system. The printer creates the model one layer at a time by spreading a layer of powder (plaster, or resins) and inkjet printing a binder in the cross-section of the part. The process is repeated until every layer is printed. This technology is the only one that allows for the printing of full color prototypes. This method also allows overhangs. It is also recognized as the fastest method.

Working

The process is similar to the Selective Laser Sintering (SLS) process, but instead of using a laser to sinter the material, an ink-jet printing head deposits a liquid adhesive that binds the material. Material options, which include metal or ceramic powders, are somewhat limited but are inexpensive relative to other additive processes. 3D Printing offers the advantage of fast build speeds, typically 2-4 layers per minute. However, the accuracy, surface finish, and part strength are not quite as good as some other additive processes. 3D Printing is typically used for the rapid prototyping of conceptual models (limited functional testing is possible).

The 3D printing process begins with the powder supply being raised by a piston and a leveling roller distributing a thin layer of powder to the top of the build chamber. A multi-channel ink-jet
print head then deposits a liquid adhesive to targeted regions of the powder bed. These regions of powder are bonded together by the adhesive and form one layer of the part. The remaining free standing powder supports the part during the build. After a layer is built, the build platform is lowered and a new layer of powder added, leveled, and the printing repeated. After the part is completed, the loose supporting powder can be brushed away and the part removed. 3D printed parts are typically infiltrated with a sealant to improve strength and surface finish.

![3D Printing Diagram](image)

**Figure 1  3 Dimensional Printing**

**Color 3D Printing**

The 3D printers from Z Corporation jet color binders onto powdered, composite materials one layer at a time, enabling the fabrication of fully printed prototypes. All the gears and rods in this demonstration model were created in place as a single unit from bottom to top. At the end of the job, the excess powder was removed between the gears. When any single gear is moved manually, all the others rotate simultaneously.

**Application**

3D printing technology is currently being studied by biotechnology firms and academia for possible use in tissue engineering applications where organs and body parts are built using inkjet...
techniques. Layers of living cells are deposited onto a gel medium and slowly built up to form three dimensional structures. Several terms have been used to refer to this field of research: Organ printing, bio-printing, and computer-aided tissue engineering among others. 3D printing can produce a personalized hip replacement in one pass, with the ball permanently inside the socket, and even at current printing resolutions the unit will not require polishing.

More recently, the use of 3D printing technology for artistic expression has been suggested. Artists have been using 3D printers in various ways.

The use of 3D scanning technologies allow the replication of real objects without the use of molding techniques, that in many cases can be more expensive, more difficult, or too invasive to be performed; particularly with precious or delicate cultural heritage artifacts where the direct contact of the molding substances could harm the surface of the original object.

From CAT scans and MRIs to physical 3D models, surgeons can preview a patient's bones and organs and save hours of time at the operating table. In addition, 3D printers can make generic and custom implants. The model of a human spine (top) was created by Objet's PolyJet technology.

Typical applications are:

- Concept models
- Parts for limited functional testing
- Color models for FEA and other engineering related applications
- Architectural & landscape models
- Color industrial design models, especially consumer goods & packaging
- Castings
Figure 2 Part model image from software in 3D printing machine

Figure 3 Part model image from software in 3D printing machine
<table>
<thead>
<tr>
<th><strong>SUMMARY</strong></th>
</tr>
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<tbody>
<tr>
<td><strong>Abbreviation:</strong></td>
</tr>
<tr>
<td><strong>Material type:</strong></td>
</tr>
<tr>
<td><strong>Materials:</strong></td>
</tr>
<tr>
<td><strong>Max part size:</strong></td>
</tr>
<tr>
<td><strong>Min feature size:</strong></td>
</tr>
<tr>
<td><strong>Min layer thickness:</strong></td>
</tr>
<tr>
<td><strong>Tolerance:</strong></td>
</tr>
<tr>
<td><strong>Surface finish:</strong></td>
</tr>
<tr>
<td><strong>Build speed:</strong></td>
</tr>
<tr>
<td><strong>Applications:</strong></td>
</tr>
</tbody>
</table>
AIM: To Study and Experiment on Fused Deposition Modelling Process

Fused Deposition Modelling

The FDM process was originally developed by Advanced Ceramics Research (ACR) in Tucson, Arizona, but the process has been significantly advanced by Stratasys, Inc. FDM is a non-laser filament extrusion process that utilizes engineering thermoplastics, which are heated from filament form and extruded in very fine layers to build each model from the bottom up. The models can be made from acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polyphenylsulfone (PPSF), and various versions of these materials. Furthermore, the models are tough enough to perform functional tests. The extrusion-based process utilizes filaments of molten thermoplastic that are extruded from a heated tip to build up layers comprising the physical model. As shown in Figure the Extrusion head in which the material is pulled off the spool, heated just above the melting temperature, and deposited at the desired location.

Application of FDM technology includes Conceptual Modelling, Fit, form applications and models for further manufacturing procedures, Investment casting and injection moulding.

The key steps are:

1. Starting with the filament being fed into the drive wheels
2. The drive wheels force the filament into the liquefier
3. The heater block melts the filament
4. The solid filament is used as a linear piston
5. The melted filament is forced out through the tip

The material used is fed into the head in solid wire form and then liquefied in the head and deposited through a nozzle in liquid form. The extrusion head is able to move in the X–Y plane and is controlled to deposit very thin beads of molten material onto the build platform to form the first layer. The platform is maintained at a lower temperature to ensure the deposited thermoplastic hardens quickly in 0.1 s. After the platform lowers, the extrusion head deposits a second layer upon the first. The material then cools and solidifies in place. The speed of the drive wheels can determine the width of the extrusion path that is controlled using the software.
build process lays down both modeling and support material in separate steps for one layer at a time. To switch between modeling and support material, one nozzle will raise up so it will not interfere with the material being laid down. The appropriate amount of Z-axis movement is determined by a setting within the software. The heads are moved in the X–Y plane by a set of linear motors to improve resolution, which hang from the machine ceiling.

This process is repeated and alternates between build and support materials until the part is completed. The support material is then removed and the part is cleaned. The selection of the material for support is important. Built materials used include ABS, Polycarbonate, Elastomers, Polyethylene Polypropylene.

The use of water-soluble material is very convenient as it is easy to remove those structures. This process is office friendly, does not make noise during build, produces parts with comparable speeds, and very small parts can be manufactured. In recent years improvements in the surface
finish have also been obtained. The ultrasonic-based water-soluble material is very noisy, and thus should be placed in an isolated room.

Although this process is classified as a solid process, due to the nature of the material, the process actually lays down ribbons of material creating a secure bond from layer-to-layer. Support material may be removed in two different ways. BASS stands for Break Away Support Structure. The support is broken away manually and the model is then cleaned with sand paper and tools. Water Works is a method that removes the support material automatically in a water-based solution. This automates the process to free up time, and it also results in a model with greater surface finish smoothness and feature detail.

Steps in Rapid prototyping (FDM)

1) Modeling in a Pro/E software
2) Conversion into STL format

3) co-ordinates generated for different facet

    solid PRT0003
    facet normal 9.951845e-01 -9.801992e-02 0.000000e+00
    outer loop
    vertex 8.935302e+01 4.119510e+01 2.540000e+01
    vertex 8.935302e+01 4.119510e+01 0.000000e+00
    vertex 8.947504e+01 4.243393e+01 2.540000e+01
    endloop
    endfacet
    facet normal 9.569404e-01 -2.902845e-01 0.000000e+00
    outer loop
    vertex 8.935302e+01 4.119510e+01 2.540000e+01
Main process parameters

1. **Orientation**: Part builds orientation or orientation referrers to the inclination of part in a build platform with respect to X, Y, Z axis. Where X and Y-axis are considered parallel to build platform and Z-axis is along the direction of part build.

2. **Layer thickness**: It is a thickness of layer deposited by nozzle and depends upon the type of nozzle used.

3. **Contour width**: The width of contour deposited by nozzle.

4. **Part raster width** (raster width): Width of raster pattern used to fill interior regions of part curves.

6. **Raster angle**: It is a direction of raster relative to the x-axis of build table.

7. **Shrinkage factor**: Shrinkage factor applied in the x, y and z direction.

8. **Perimeter to raster air gap**: The gap between inner most contours and the edge of the raster fill inside of the contour.

9. **Raster to raster gap** (air gap): It is the gap between two adjacent rasters on same layer.
Parameter adjustment in software

Comparision of FDM with Sterolithography and 3DP

<table>
<thead>
<tr>
<th>Property Name</th>
<th>Fused Deposition Modeling</th>
<th>Stereolithography</th>
<th>Three Dimensional Printing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min layer thickness (in.)</td>
<td>0.0050</td>
<td>0.0010</td>
<td>0.0020</td>
</tr>
<tr>
<td>Tolerance (in.)</td>
<td>±0.0050</td>
<td>±0.0050</td>
<td>±0.0040</td>
</tr>
<tr>
<td>Surface finish</td>
<td>Rough</td>
<td>Smooth</td>
<td>Rough</td>
</tr>
<tr>
<td>Build speed</td>
<td>Slow</td>
<td>Average</td>
<td>Very Fast</td>
</tr>
<tr>
<td>Applications</td>
<td>Form/fit testing, Function testing, Rapid tooling patterns, Small detailed parts, Presentation models, Patient and food applications, High heat applications</td>
<td>Form/fit testing, Functional testing, Rapid tooling patterns, Snap fits, Very detailed parts, Presentation models, High heat applications</td>
<td>Concept models, Limited functional testing, Architectural &amp; landscape models, Color industrial design models, Consumer goods &amp; packaging</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>FDM</td>
<td>SLA</td>
<td>3DP</td>
</tr>
<tr>
<td>--------------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td><strong>Material type</strong></td>
<td>Solid (Filaments)</td>
<td>Liquid (Photopolymer)</td>
<td>Powder</td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td>Thermoplastics such as ABS, Polycarbonate, and Polyphenylsulfone; Elastomers</td>
<td>Thermoplastics (Elastomers)</td>
<td>Ferrous metals such as Stainless steel; Non-ferrous metals such as Bronze; Elastomers; Composites; Ceramics</td>
</tr>
<tr>
<td><strong>Max part size (in.)</strong></td>
<td>36.00 x 24.00 x 36.00</td>
<td>59.00 x 29.50 x 19.70</td>
<td>59.00 x 29.50 x 27.60</td>
</tr>
</tbody>
</table>
Aim: Study of stereo lithography process

The stereo lithography (SL or SLA) is an additive manufacturing technology for producing models, prototypes, patterns, and in some cases, production parts. It is a first RP technique and is still most widely used. The term “stereolithography” was coined in 1986 by Charles (chuck) W. Hull. Stereolithography was defined as a method and apparatus for making solid objects by successively “printing thin layers of the ultraviolet curable material one on top of the other”. Hull described a concentrated beam of ultraviolet light focused onto the surface of a vat filled with liquid photopolymer. The light beam draws the object onto the surface of the liquid layer by layer, causing polymerization or crosslinking to give a solid. This is the complex manufacturing process so its control must be done by use of computer.

PROCESSER:

Stereolithography is an additive manufacturing process using a vat of liquid UV-curable photopolymer “resin” and a UV laser to build parts a layer at a time. On each layer, the laser beam traces a part cross section pattern on the surface of the liquid resin. Exposure to the UV laser light cures, solidifies the pattern traced on the resin and adheres it to the layer below.
After a pattern has been traced, the SLA’s elevator platform descends by a single layer thickness, typically 0.05 mm to 0.15 mm (0.002” to 0.006”). Then a resin filled blade sweeps across the part cross section, re-coating it with fresh material. On this new liquid surface, the subsequent layer pattern is traced, adhering to the previous layer. A complete 3-D part is formed by this process. After building, parts are cleaned of excess resin by immersion in a chemical bath and then cured in a UV oven.

Stereolithography requires the use of support structure to attach the part to the elevator platform and to prevent certain geometry from not only deflecting due to gravity, but to also accurately hold the 2-D cross sections in place such that they resist lateral pressure from the re-coater blade. Supports are generated automatically during the preparation of 3-D CAD models for use on the stereolithography machine, although they may be manipulated manually, this is not true for all rapid prototyping technologies.

**Avantages And Disadvantages:-**

- Inexpensive compared to other techniques.
- Uses light-sensitive liquid polymer.
- Requires post-curing since laser is not of high enough power to complete.
- Long-term curing can lead to warping.
- Parts are quite brittle and have a tacky surface.
- No milling step so accuracy in Z can suffer.
- Support structures are typically required.
- Process is simple: There are no milling or masking steps required.
- Uncured material can be toxic. Ventilation is a must.
Experiment No - 9

Aim - Study of Solid Ground Curing (SGC)

Introduction

Solid Ground Curing, also known as the Solider Process, is a process that was invented and developed by Cubital Inc. of Israel. The overall process is illustrated in the figure and the steps are illustrated below. The SGC process uses photosensitive resin hardened in layers as with the Stereo-lithography (SLA) process. However, in contrast to SLA, the SGC process is considered a high-throughput production process. The high throughput is achieved by hardening each layer of photosensitive resin at once. Many parts can be created at once because of the large work space and the fact that a milling step maintains vertical accuracy. The multi-part capability also allows quite large single parts (e.g. 500 × 500 × 350 mm / 20 × 20 × 14 in) to be fabricated. Wax replaces liquid resin in non-part areas with each layer so that model support is ensured.

Fig: Solid Ground Curing

Principle of Operation

Developed by cubital(Israel), solid ground curing is something of a hybrid between stereo-lithography and laser printing. The machine makes an image of cross-section of the model on glass plate, using similar methods to those employed in a laser printer. The surface of the liquid
polymer is solidified by exposing it to light from UV lamp (similar to stereo- lithography), using the glass plate as a mask which allows the light through to expose the light surface in selected area. Unlike SLA, SGC cures an entire layer at a time.

**Process Description**

Figure depicts solid ground curing, which is also known as the solider process.

![Schematic Diagram of Solid Ground Curing](image)

First, a CAD model of the part is created and it is sliced into layers using Cubital's Data Front End® (DFE®) software. At the beginning of a layer creation step, the flat work surface is sprayed with photosensitive resin, as shown below:

**STEP 1: Spray photosensitive resin.**
For each layer, a photo mask is produced using Cubital's proprietary ionographic printing technique, as illustrated below:

**STEP 2: Develop photomask.**

Next, the photo mask is positioned over the work surface and a powerful UV lamp hardens the exposed photosensitive resin.

**STEP 3: Expose photomask.**

After the layer is cured, all uncured resin is vacuumed for recycling, leaving the hardened areas intact. The cured layer is passed beneath a strong linear UV lamp to fully cure it and to solidify any remnant particles, as illustrated below:

**STEP 4: Vacuum uncured resin and solidify remnants.**
In the fifth step, wax replaces the cavities left by vacuuming the liquid resin. The wax is hardened by cooling to provide continuous, solid support for the model as it is fabricated. Extra supports are not needed.

**STEP 5: Wax is applied to replace uncured resin areas.**

In the final step before the next layer, the wax/resin surface is milled flat to an accurate, reliable finish for the next layer.

**STEP 6: Top surface is milled flat.**

Once all layers are completed, the wax is removed, and any finishing operations such as sanding, etc. can be performed. No post-cure is necessary.

**Advantages**

- Multiple parts can be positioned within the entire working envelop resulting high throughput;
- No support structure is required as the wax support the structure in all directions;
- Part complexity does not affect speed, however volume does;
• Each layer is fully cured resulting that the dimension is very stable with no shrinkage effect after the process and requires no post-curing process;
• Capable to build even the most complicated parts without much difficulty;
• Build session can be interrupted and erroneous layer can be erased.

Disadvantages

• The process is rather complicated which required skill person to look after and unattended operation is not possible;
• The resin consumption is disregard of size of the cross-section of the parts but only depended on the number of layers resulting that it is too expensive for parts with small cross-sectional area;
• The machine is very large and machine is noisy;
• Very few materials are available;
• High equipment cost made it not easy to be justified.

Application field

Application field of solid ground curing is similar to SLA and can produce parts with even more complicated details;

• Form-fit for assembly tests and process planning;
• Prototype for concept models;
• Models for investment casting;
• Replacement of wax pattern;
• Soft tooling;
• Medical applications.
Experiment No -10

Aim - Study of Metal Rapid Prototyping

- Need for the Metal RP

Despite many benefits, the use of many of the commercially available RP technologies in industry is not feasible due to their limited use of functional or standardized working materials. As can be observed in Table 1, the majority of RP technologies produce prototypes made of some certain and often proprietary, polymers.

<table>
<thead>
<tr>
<th>RP Technology</th>
<th>Working Principle</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stereolithography (STL)</td>
<td>UV laser is selectively scanned onto photo-sensitive polymer</td>
<td>Liquid UV photopolymers; highly toxic</td>
</tr>
<tr>
<td>Fused Deposition Modeling (FDM)</td>
<td>Plastic filament is extruded through heated nozzle</td>
<td>Wax, ABS, Elastomers</td>
</tr>
<tr>
<td>Selective Laser Sintering (SLS)</td>
<td>Using a heated laser to sinter together particles</td>
<td>Polycarbonate, Nylons, Elastomers, ceramics, some metals</td>
</tr>
<tr>
<td>Laminated Objective Manufacturing (LOM)</td>
<td>CO2 laser is used to cut cross sections out of layers of paper; layers are thermally fused together</td>
<td>Paper; similar to wood</td>
</tr>
<tr>
<td>3D printing</td>
<td>Printer head deposits molten wax onto bed of starch</td>
<td>Wax and starch, fragile and powdery</td>
</tr>
<tr>
<td>Multi-jet modeling (MJM)</td>
<td>Similar to an ink-jet printer, several print heads deposit beads of wax</td>
<td>Wax</td>
</tr>
</tbody>
</table>

Table 1: RP technology & material used

This issue of limited material selection is identified as one of the key reasons why rapid prototyping has yet to make a major advance towards rapid manufacturing. It has been a goal of many researchers in the past few years to overcome this limitation through the development of RP processes that are capable of producing metallic components. The development of a RP technology capable of creating metallic parts would herald significant advantages in manufacturing and design:
1. Objects created using RP will no longer be limited to prototypes of fit and form, but will be useful as functional prototypes; the design iteration will be greatly shortened as prototypes with materials extremely similar to the actual manufactured part will be used for analysis without expensive tooling.

2. RP will no longer be limited to the production of prototypes; instead actual parts will be able to manufactured straight from the machine.

3. For large production runs where manufacturing through RP would be too slow, the technology could be used to create tooling (molds, inserts, etc.) for the production process.

4. Due to the ability to manufacture several different parts in one batch, customized products could easily be made.

5. There also exists an opportunity to create functionally graded materials; RP’s nature of additive fabrication enables itself to the placement of different materials in specific places throughout a geometry.

6. Geometrically tailored components optimized for high strength and low mass would also be able to be manufactured.

7. As can be seen, there is a large motivation to overcome the materials limitation of current RP technologies.

- **Metal Rapid prototyping Technologies classification**

Although research in the rapid prototyping of metallic components is relatively new, there are currently numerous different directions in metal RP technology development. These technologies can be grouped according to their fundamental metal deposition working principles as seen in Figure 1.

Figure 1 Classification of Metal RP
As can be seen, the first distinction of metal RP technologies lies in the manner in which the metallic part was generated. Indirect fabrication is the use of a RP machine to generate inserts or molds for the creation of metallic parts. Also known as Rapid Tooling, indirect fabrication techniques involve creating a mold out of a standard RP material from which several hundred parts can be injection molded. Usually the RP molds must have an epoxy affixed to them in order to withstand the high temperatures of molding. Other indirect fabrication techniques involve the use of a rapidly prototyped part as a pattern for the creation of a mold.

Direct fabrication, on the other hand, is the use of a RP machine to create a functional metallic part. Many different and new technologies have been created in order to tackle this large problem. Simply, direct metal RP fabrication techniques can be divided into laser based and non-laser based technologies. Non-laser based technologies involve the selective deposition of metal material. Currently, Multiphase Jet Solidification (MJS) is the only non-laser based technique being developed. It is very similar to Fused Deposition Modeling in that it selectively deposits its preheated material through a nozzle. Laser based fabrication involves the use of a laser to selectively join the metallic material. As can be seen in Figure 1, this can be done through sintering, cladding, or binding. Laser sintering involves the use of a high powered laser to selectively melt the surfaces of pure metallic powders in order to create a “green” part. The part typically undergoes subsequent infiltration in order to create a fully dense part. Laser cladding is analogous to 3D welding. Using an extremely high-powered laser, metal particles are completely melted and selectively deposited on a substrate. Finally, laser binding generally involves the use of a laser to bind a second phase in order to hold the metallic particles together. These parts are then required to undergo a de-binding stage and a sintering stage.

- Laser Engineered Net Shaping (LENS)
- Working Principle of LENS

The working principle of the LENS process is the use of a laser to selectively clad metallic powder. A schematic of the process is provided in Figure 2.
A high-powered laser beam (typically >300W Nd:YAG) is focused on a metal substrate to create a molten weld pool. Metallic powder is then injected into the weld pool by an inert carrier gas. The powder is melted in the pool; as the laser passes by the deposit is quickly cooled, leaving behind a thin line of metal. The substrate is moved relative to the laser beam in order to deposit thin metallic lines with a finite width and thickness. Rastering of successive cross-sectional layers is done as the laser-focusing lens and powder delivery nozzle are raised along the z-axis. Once the part is complete, the substrate is removed by machining or by dissolving with chemicals. In addition to the basic hardware (laser, powder delivery apparatus, and CNC table), the system also consists of control system hardware and a cooling system for the powder nozzle. The cooling system is used for the powder nozzle because it is exposed to a thermal load by scattered and reflected laser radiation. Control system hardware includes sensors and CCD cameras in order to provide online control – an integral part of the process. The major strength of the LENS process is its ability to deposit a multitude of materials. Since the material deposition relies only on the feeding of a powder or wire, it is relatively simple to use multiple kinds of materials. Currently titanium, nickel, cobalt, steel, and aluminum can be deposited with LENS. In fact, recent research has shown that LENS is capable of manufacturing binary functionally graded materials. The LENS process does have some weaknesses, however. While LENS is lauded for its planar accuracy (+/- 0.005") and its ability to manufacture thin-walled parts, it is only capable of producing “near net shape” components because of its poor accuracy in the build direction (0.015"). Also, unlike standard RP technologies, LENS does not have the ability to generate support structures for complex geometries featuring overhangs. As such, the geometry able to be created by the LENS process is limited; the maximum angle achieved in a single width deposition is 30°, and about 15° for solid parts. However, research on the development of a multi-
axis LENS machine is underway. The deposition rate of LENS is quoted as 0.5 cubic inches per hour.

- **Advantages and Disadvantages of the LENS Process**

To summarize the LENS process, and the laser cladding process in general, the following list of advantages and disadvantages is presented.

*Advantages*

- Capable of depositing numerous materials
- Good accuracy in build plane; capable of producing thin walls and ribs
- Material properties are improved over casting
- 50% material usage (compared to 5-20% for standard forging and machining)
- Capable of producing functionally graded materials
- 100% dense parts

*Disadvantages*

- Poor accuracy in growth direction
- Poor surface finish
- Cannot to do complex geometry
- In need of more specialized process control for reliable deposits

- **Selective Laser Sintering (SLS)**

  - **Working Principle of SLS**
  
  Looking back to Figure 1, it is observed that Selective Laser Sintering (SLS) is listed under three different categories of RP metal fabrication: as an indirect fabrication method, as a laser sintering method, and as a laser binding method. This technology is one of RP’s most robust. This technology’s working principle is the use of a CO2 laser to fuse and sinter metallic powder one layer at a time (see Figure 6).
Advantages

• Accurate deposition both in-plane and in growth direction
• Net shape parts
• Capable of generating complex shapes without the need to remove support structures

Disadvantages

• Plagued by porosity
• Some shrinkage; part accuracy suffers
• Only a few metal-like substances; proprietary metal compounds

- **Multiphase Jet Solidification (MJS)**

- Working Principle of MJS

The working principle of Multiphase Jet Solidification (MJS) is shown schematically in Figure below.

![Figure 12 – Working Principle of the MJS Process](image)

A powder-binder mixture is passed through the machine as feedstock, where it is first heated above its solidification point to achieve a suitable viscosity. It is then squeezed out of nozzle by a pumping system and deposited layer by layer (the deposition head unit is mounted on a xyz-table...
that is controlled by a computer system). The molten material solidifies once in contact with the platform or the previous layer due to the decrease in temperature and pressure. The contact of the liquefied material leads to partial remelting of the previous layer and a good bonding between the layers. Critical process parameters to successful deposition are the speed of the deposition nozzle, and the flow rate of the material. In order to make a functional metal part, the green part made via the deposition (typically 50-70% percent volume solid material) must then undergo a debinding step and a sintering step, as shown in Figure 13.

![Image of the MJS Process Chain](image)

**Figure 13** – Schematic of the MJS Process Chain.

The debinding stage occurs with a solvent or through thermal decomposition, thus transforming the green part into a brown part. After the subsequent sintering, the final part density is 95-98%.

### 5.2 Material Properties of Parts Produced by MJS

Materials successfully tested with MJS include 316L, M4T2, FENi, Ti, Stellite (Co-Cr-Mo), and Sic. One large advantage with MJS is that it is able to use a broad range of materials; due to its similarities with metal injection molding (MIM), researchers are hoping that the long materials list of this successful technology will be carried over to MJS. The main restrictions for materials are that they must have a suitable viscosity, around 10 to 200 Pa, and a binder melting temperature of less than 200°C. A comparison of material properties between MIM and MJS parts is provided in Table 5.

<table>
<thead>
<tr>
<th>Process and Material</th>
<th>Density (% of theoretical)</th>
<th>Ultimate Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIM 316L, typical values</td>
<td>95-99.8</td>
<td>450-520</td>
</tr>
<tr>
<td>MJS 316L</td>
<td>97-99.3</td>
<td>480</td>
</tr>
</tbody>
</table>
It should be noted that the powder-binder often observed in MIM is not a problem with MJS due to the lower velocity with which the material exits from the nozzle. The homogeneous structure and good bonding between the layers found in MJS is illustrated through the investigation of its microstructure. The largest problem with this technology is the large amount of shrinkage (10-16%) that arises from the sintering stage. In order to avoid this shrinkage, the brown part can be infiltrated with liquid metal. The infiltrant must be harmonized with the matrix material with regard to melting temperature, wetting behavior, etc. This technique also improves the mechanical properties of the final part. The achievable accuracy of the green parts is +/- 0.2mm. The accuracy of the final part depends to a large extent on post processing, e.g. debinding and sintering. The maximum wall thickness is limited to 15mm due to the debinding step. Fundamentally, the surface quality depends on the layer thickness. The layer-based fabrication process inherently leads to rough surfaces (the stair-step effect), however, the green parts can be easily machined or sanded to a smooth surface finish before sintering.

Other methods described in classification are same as process for other material. Few other Methods used in Metal RP introduced briefly below,

- **OTHER METAL RP TECHNOLOGIES**
  In this the technologies yet to be presented from Figure 1 are briefly discussed. The majority of these technologies are in their infancy; as such, their accompanying literature focuses on the working principle and not on the associated material properties.

1. **3D Printing**
   This technology involves the use of a printer head to selectively deposit a binder polymer over a bed of metal powder. The selectively bound part, when later removed from the bed, is a relatively low-density (about 50%) “green” part. The green part is then subsequently fired and infiltrated to make a dense metal part. Stainless steel-bronze parts have been made with this technology.

2. **Shape Deposition Manufacturing (SDM)**
   This technology combines laser cladding (as in the LENS process) with subtractive machining. A laser is used to melt powdered metal in order to deposit metal; a milling machine is then used to
create a near-net shape component. This process has been proven to successfully make functionally graded materials.

3. Laminated Object Manufacturing (LOM)
This technology has been traditionally used to cut stacks of paper layers with a laser. Recent research from Japan shows interest in using the same technology to create metal parts from several layers of cut sheet metal.

4. Ultrasonic Object Consolidation (UOC)
This technology utilizes solid-state joining techniques to deposit layers of tape to form solid aluminum parts. The process involves depositing several layers of aluminum tape, followed by a trimming step in order to produce near-net shape parts. The process is extremely fast but is currently limited to aluminum. There exist limits on the aspect ratio of the part due to the trimming stage of the process. The bonds between each layer of the part also provide anisotropic material properties. Also, this technology does not enjoy the freedom to build complex geometries, such as overhanging structure, cannot be built.

5. Optoform
A newer RP technology, Optoform uses viscous pastes as its working material. Similar to SLA, Optoform uses a UV laser to solidify the paste layer by layer. The material is composed of resin, some fillers, and a photoinitiator. The building speed is 18 about 25 mm/hour, and there is no waiting time during the recoating. After building on the Optoform machine, post-processing is required consisting of debinding and sintering steps. Currently two types of polymers and one ceramic material are commercially offered. Research on the production of metal parts with this technology has been recently abandoned because of the poor resultant material properties.
EXPERIMENT NO.: 11

Aim: STUDY OF CONVERSION OF STL FILE.

In conventional machining techniques, the part is manufactured by removal of the material layer-by-layer, which is exactly the opposite of rapid prototyping. Hence, there are many issues that have to be taken into account, like the tooling, the toolpath determination, and feeding the information regarding the toolpath, which may involve tedious programming, setting up the workpiece for machining, etc. Therefore, all these issues require extensive planning and preparation in advance. RP is faster because it takes virtually no human effort to run the machine. After the virtual model has been made, only a few simple buttons need to be pushed to begin the rapid prototyping, thus the operator can go off and work on something else. By machining a prototype, the process may become limited by tools available or space needed for the tools. When building a rapid prototype, since the model is built in layers, almost all structures can be built without a problem.

A TYPICAL RAPID PROTOTYPING PROCESS

There are many different RP processes, but the basic operating principles are very similar. Figure 1 shows the data-flow diagram of the basic process. It includes the following steps:

1. Construct the CAD model
2. Convert the CAD model to STL format
3. Check and fix STL file
4. Generate support structures if needed
5. Slice the STL file to form layers
6. Produce physical model
7. Remove support structures
8. Post-process the physical model

FIGURE 1. The data flow of the basic RP process
The RP input can be described as the electronic information required to specify the physical object with 3D data. There are two possible starting models, i.e., a computer model and a physical model. A computer model created from a CAD system can be either a surface model or a solid model. A physical model can be obtained by digitizing or scanning the geometry of a physical part. Three-dimensional data from digitizing a physical part is not always straightforward. It generally requires data acquisition through a method known as reverse engineering, using a CMM or laser digitizer.

The industry standard for rapid prototyping is the STL file, a file extension from Stereolithography. Basically, it is a file that uses a mesh of triangles to form the shell of the solid object, where each triangle shares common sides and vertices. The CAD software generates a tessellated object description. In STL format, the file consists of the X, Y, and Z coordinates of the three vertices of each surface triangle, with an index to describe the orientation of the surface normal. Normally, the support structure is generated before slicing to hold overhanging surfaces during the build.

Most current CAD packages can export a CAD file in STL file format, and good STL files will assure a speedy quote turnaround, and good quality RP models. The STL format is an ASCII or binary file used in the RP process. It is a list of triangular surfaces that describe a computer-generated solid model. The binary files are smaller when compared to ASCII files. The facets define the surface of a 3D object. As such, each facet is part of the boundary between the interior and the exterior of the object. The orientation of the facets (which way is “out” and which way is “in”) is specified redundantly in two ways that must be consistent. First, the direction of the normal is outward. Second, the vertices are listed in counterclockwise order when looking at the object from the outside (right-hand rule) as shown in Figure 2.

![Figure 2](image)

**FIGURE 2.** The triangle with three vertices. The sequence of the storage of the vertices indicates the direction of the triangular face
WHY STL FILES?

The STL files translate the part geometry from a CAD system to the RP machine. All CAD systems build parts and assemblies, store geometry, and generally do many things in their own independent and proprietary way. Instead of having a machine that has to communicate with all of these different systems, there is a single, universal file format that every system needs to be able to produce so that an RP machine can process what a part looks like for slicing. This is the STL file.

Why is STL format used? The reason is because slicing a part is easier compared to other methods such as B-rep (boundary representation) and CSG (constructive solid geometry), which will need geometric reasoning and data conversion. Figure 3 shows the representation of a cube in B-rep. The right-hand side of the figure shows the data structure of the geometric entities. To calculate the interaction between the geometry and a plane that represents the slicing operation is not very efficient. The slicing operation is computed by “intersecting” a ray of virtual lines with the object of interest. In other words, it is necessary to compute the intersections between a lot of lines and the object. The STL format allows us to transfer the slicing operation into a routine of finding the interactions between lines and triangles. Basically, this operation judges whether the intersection point is within or outside the triangles, and there are very efficient codes to do just that.

FIGURE 3 Boundary representation of a cube and its data structure

The reason that the STL format is the industry standard is because it can make the process robust and reliable to get the correct result the first time, and because high-end data processing tools, such as surface and STL repair and translation tools, are available in the market.

The model presenting the physical part to be built should be presented as closed surfaces that define an enclosed volume. The meaning of this is that the data must specify the inside, outside, and boundary of the model. This requirement is redundant if the modeling used is solid modeling. This approach ensures that all horizontal cross-sections essential to RP are closed curves. The internal representation of a CAD model as shown in Figure 4 can be in B-rep or CSG representations, while its STL representation is shown in Figure 5. The STL representation is often used as the standard format to interact between the CAD model and an RP machine. The
STL representation approximates the surfaces of the model by polygons, meaning that STL files for curved parts can be very large in order to represent the original geometry well.

In other words, the CAD models can have smooth curved surfaces, but the RP process must have the model broken down into discrete volumes to build the part. To have a continuous smooth curved surface, the volumes for each discrete piece would have to be close to zero, which would require the number of entities to be infinite, which makes for a very large file size in the real world. In order to minimize the file size to something that is more manageable, the system makes the volumes of the discrete pieces larger.

FIGURE 4 An example of a CAD model

FIGURE 5. An example of an STL triangulation model
The larger these volumes, the fewer are needed to approximate the part. Keep in mind that the fewer the pieces used, the less accurate the approximation is when compared to the original model. Triangulation, as shown in Figure 5, is breaking the model into these discrete pieces and the trick is balancing the number and size of these pieces to make a practical file size without sacrificing too much accuracy.

**CONVERTING STL FILE FROM VARIOUS CAD FILES**

Most of the current CAD software can directly output an STL file from a CAD model, but the actual command may change depending on various versions. The following examples are the methods used for generating an STL file in various CAD files. Note that these procedures are likely going to be version dependent, and thus the purpose here is to provide a reference.

(1) Making STL files from SolidWorks
1. Click on File, Save As. Select the path to save the file.
2. For File Type, use the drop-down arrow, choose STL. Click Options.
3. Options—select Binary for file type. Binary files are approximately 1=5 the size of ASCII files.
4. Options—Total Quality: Choices are Coarse, Fine, and Custom. Choosing Custom allows access to Total Quality and Detail Quality sliders and fields. In most cases, selecting Fine will produce an acceptable file, for custom try entering 0.001 in. or 0.002 in. for Deviation, and 108 for Angle Tolerance.
5. Check the “Show STL Info Before File Saving” or “Preview” box to see a faceted view of the STL file.
6. Select Done, and send the file to the RP machine.

(2) Making STL files from Pro/Engineer
1. Click on file, save copy.
2. Select the file type STL.
3. In the Export STL dialog box, set Format to Binary. Binary files are about 1/5 the size of ASCII files.
4. Set the Chord Height to 0.001 in. The field will be replaced by a minimum acceptable value for the geometry of the model.
5. Set Angle Control to 0.5.
6. Name the file and click the OK button. Pro=Engineer will save your STL file, and display your triangles on the screen.

(3) Making STL files from Unigraphics
1. Select File, Export, then Rapid Prototyping.
2. Make sure it is binary, set triangle to 0.001 in. or 0.025 mm.
3. Type in the file name, make sure the extension is stl, then select OK.
4. In class selection, select all, then OK.
5. Then discontinue, then OK.

When generating the STL files, triangular surfaces are used to express the real surfaces of the part. To explain the concept of STL tolerance, Figure 6 is used. The left figure shows a rectangle
representing the circle and the right figure shows an octagon representing the circle. In order to measure the closeness between each of them, two techniques are used. The first involves measuring the distance between the tangent to the circle and the side of polygon. Another technique is to find the angle made by the tangent to the circle and the side of the polygon. The latter method serves as a good measure of the degree to which the polygon represents the circle well. As a rule of thumb, triangles of a size between 0.02 mm (0.001 in.) and 0.05 mm (0.002 in.) will produce a good STL file.

There are two ways for users to control the tolerance of the triangulated model, which can also be explained by the following example as shown in Figure 7. The users can input the maximum acceptable angle between the model line and the tangent of the original curve. The users can also input the maximum acceptable distance between the model line and the original curve. As the two figures show, it is easy to find that the smaller the maximum value input by users, the closer the model line will be to the original curve, and consequently the smaller the tolerance will be.

![Diagram showing two methods for STL approximation](image)

Method 1: \( A > B \)

Method 2: \( a > b \)

Thus, the octagon is a better representation of the circle.

FIGURE 6 The tolerance between a circle and an octagon representation of the circle

![Diagram showing maximum distance](image)

Maximum distance

![Diagram showing maximum angle](image)

Maximum angle

FIGURE 7 Two ways of STL approximation: Upper figure (chord height control): maximum acceptable distance between the model line and the original curve. Lower figure (angle control): maximum acceptable angle between the model line and the tangent of the original curve.