RAPID PROTOTYPING TECHNOLOGY AND ITS APPLICATIONS

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Abstract - *Now a days, one of the critical factors in competitive technology is "time to market" along with full proof design. This critical factor indicates the entire product design cycle from concept to product design to prototype to manufacturing process design to actual implementation. In this product design and development process, the prototyping or model making is one of the important step to finalize a product which helps in conceptualization of a design. Thus, we adopt the method of Rapid Prototyping (RP) for the design and development of small prototypes or models of large items to check for errors before actually making them. The technology which considerably speeds the interactive product development process is the concept and practice of Rapid Prototyping (RP) also called Solid Freeform Fabrication (SFF). This paper provides a better platform for researchers, new learners and product manufacturers for various applications of RP models. Subsequently it creates awareness among the people of recently developing RP method of manufacturing in product design, developments and its applications.*

***Keywords* –** CAD Model, Stereolithography, Selective Laser Sintering, Fused Deposition Modeling, Laminated Object Manufacturing, Tessallation, Prototype

Introduction

A technology wherein the physical modeling of a design is done using a specialized machining technology, Rapid Prototyping (RP) by layer-by-layer material deposition started during early 1980s with the enormous growth in Computer Aided Design and Manufacturing (CAD/CAM) technologies when almost unambiguous solid models with knitted information of edges and surfaces could define a product and also manufacture it by CNC machining. It is also known by several other names like digital fabrication, 3D printing, solid imaging, solid free form fabrication, layer based manufacturing, laser prototyping, free form fabrication, and additive manufacturing.[1] The historical development of RP and related technologies is presented in table 1.

Year of Inception	Technology
1770	Mechanization
1946	First computer
1952	First numerical control (NC) machine tool
1960	First commercial laser
1961	First commercial Robot
1963	First interactive graphics system(early version of computer aided design)
1988	First commercial rapid prototyping system

Table 1: Historical development of Rapid Prototyping and related technologies

RP has been high prospective to reduce the cycle and cost of product development. It is an important tool in digital manufacturing in rapid product development. There are a variety of methods that can be used in RP to deposit the material for creating a proto model through RP technique. **Since 1988, more than 20 rapid prototyping techniques have emerged.** Some of the important methods are used in industries for manufacturing the product model such as Stereolithography (SLA), Selective Layer Sintering (SLS), 3D Printing (3DP), Fused Deposition Modelling (FDM).

BASIC PRINCIPLE OF RAPID PROTOTYPING

Rapid Prototyping (RP) involves automated fabrication of intricate shapes from CAD data using a layer-by-layer principle. These "three dimensional printers" allow designers to quickly create tangible prototypes of their designs, rather than just two dimensional pictures. Such models make excellent visual aids for communicating ideas with co-workers or customers and can also be used for testing purposes. For example, an aerospace engineer might mount a model airfoil in a wind tunnel to measure lift and drag forces.

The process starts with 3D modeling of the product and then STL file is exported by **Tessellating the geometric 3D model**. In Tessellation various surfaces of a CAD model are piecewise approximated by a series of triangles (figure 1) [2] and co-ordinate of vertices of triangles and their surface normals are listed. The number and size of triangles are decided by facet deviation or chordal error as shown in figure 1. These STL files are checked for defects like flip triangles, missing facets, overlapping facets, dangling edges or faces etc. and are repaired if found faulty. Defect free STL files are used as an input to various slicing softwares. At this stage choice of part deposition orientation is the most important factor as part building time, surface quality, amount of support structures, cost etc. are influenced. Once part deposition orientation is decided and slice thickness is selected, tessellated model is sliced and the generated data in standard data formats like SLC (stereolithography contour) or CLI (common layer interface) is stored.

This information is used to move to step 2, i.e., generation of physical model. The software that operates RP systems generates laser-scanning paths (in processes like Stereolithography, Selective Laser Sintering etc.) or material deposition paths (in processes like Fused Deposition Modeling). This step is different for different processes and depends on the basic deposition principle used in RP machine. Information computed here is used to deposit the part layer-by-layer on RP system platform.

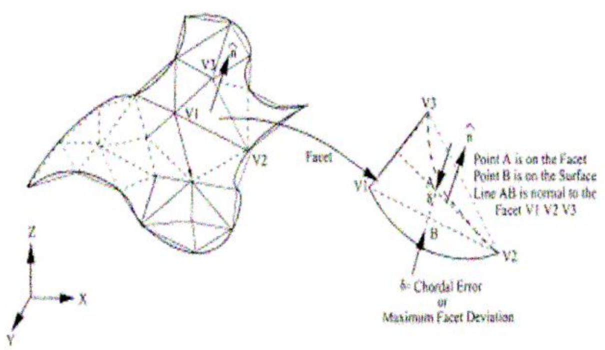


Figure 1: The tessellation of a typical surface of CAD model [2](after pandey et al. 2003b)

The final step in the process chain is the post-processing task. At this stage, generally some manual operations are necessary therefore skilled operator is required. In cleaning, excess elements adhered with the part or support structures are removed. Sometimes the surface of the model is finished by sanding, polishing or painting for better surface finish or aesthetic appearance. Prototype is then tested or verified and suggested engineering changes are once again incorporated during the solid modeling stage. Thus the steps involved in the process can be summed up as –

- Creation of the CAD model of the (part) design
- Conversion of CAD model into Standard Tessellation Language (STL) Format
- Slicing of STL file into thin sections
- Building part layer by layer
- Post processing/finishing/joining

RAPID PROTOTYPING TECHNOLOGIES

Here, few important RP processes namely Stereolithography (SL), Selective Laser Sintering (SLS), Fused Deposition Modeling (FDM) and Laminated Object Manufacturing (LOM) are described.

STEREOLITHOGRAPHY

In this technology, the part is produced in a vat containing a liquid which is a photo-curable resin acrylate. [3]Under the influence of light of a specific wavelength, small molecules are polymerized into larger solid molecules. The SLA machine creates the prototypes by tracing the layer cross sections of the surface of the liquid polymer pool with a laser beam. In the initial position the elevator table in the vat is in the top most position. The laser beam is driven in X-Y direction by the means of a programme driven mirrors to sweep across the liquid surface so as to make it solidified across the designed depth (say 1 mm). In the next cycle the elevated table is lowered further. This is repeated untill the desired 3D model is created. The arrangement for stereolithography is shown below-

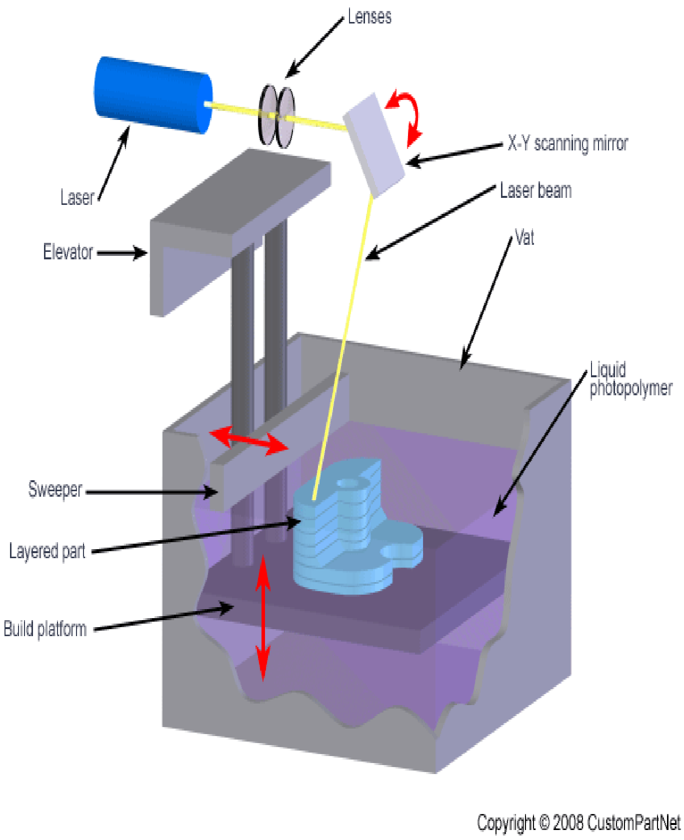


FIGURE 2 : STERELITHOGRAPHY

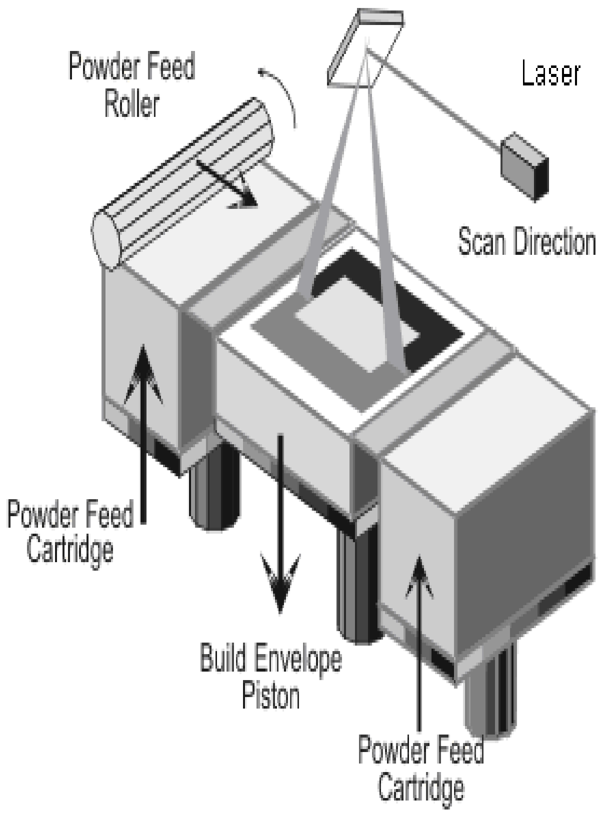


Figure 3: Selective Laser Sintering System

SELECTIVE LASER SINTERING –

[3]In Selective Laser Sintering (SLS) process, fine polymeric powder like polystyrene, polycarbonate or polyamide etc. (20 to 100 micrometer diameter) is spread on the substrate using a roller. Before starting CO2 laser scanning for sintering of a slice the temperature of the entire bed is raised just below its melting point by infrared heating in order to minimize thermal distortion (curling) and facilitate fusion to the previous layer. The laser is modulated in such away that only those grains, which are in direct contact with the beam, are affected. Once laser scanning cures a slice, bed is lowered and powder feed chamber is raised so that a covering of powder can be spread evenly over the build area by counter rotating roller. In this process support structures are not required as the unsintered powder remains at the places of support structure. It is cleaned away and can be recycled once the model is complete. The schematic diagram of a typical SLS apparatus is given in figure 3.

FUSED DEPOSITION MODELING

In Fused Deposition Modeling (FDM) process a movable (x-y movement) nozzle on to a substrate deposits thread of molten polymeric material. The build material is heated slightly above (approximately 0.5 C) its melting temperature so that it solidifies within a very short time (approximately 0.1 s) after extrusion and cold-welds to the previous layer as shown in figure 8. Various important factors need to be considered and are steady nozzle and material extrusion rates, addition of support structures for overhanging features and speed of the nozzle head, which affects the slice thickness. More recent FDM systems include two nozzles, one for part material and other for support material. The support material is relatively of poor quality and can be broken easily once the complete part is deposited and is removed from substrate. In more recent FDM technology, water-soluble support structure material is used. Support structure can be deposited with lesser density as compared to part density by providing air gaps between two consecutive roads.

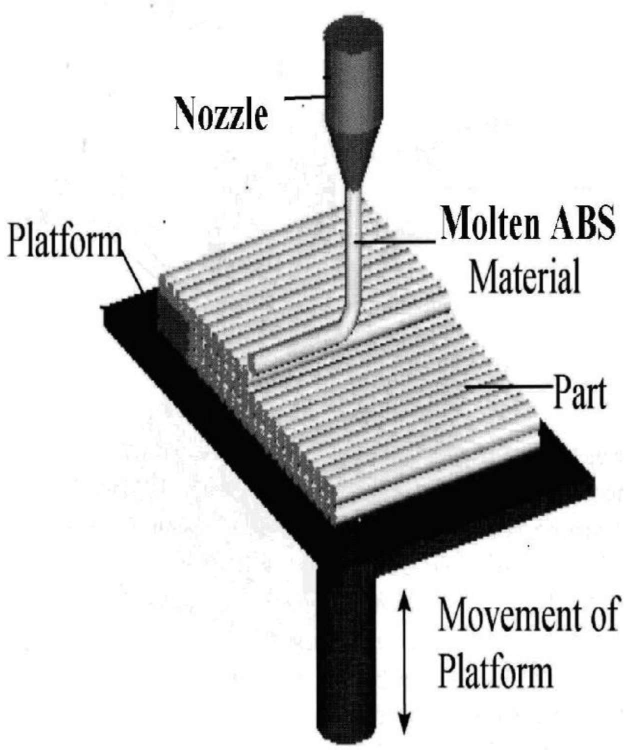


FIGURE 4: FUSED DEPOSITION MODELLING PROCESS[3] (after pham and demov,2001)

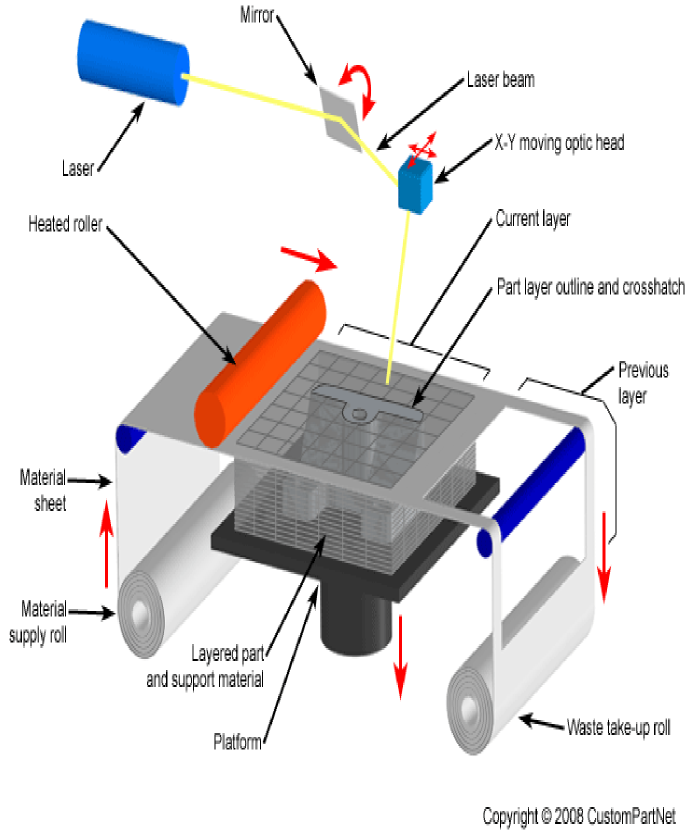


FIGURE 5 : LAMINATED OBJECT MANUFACTURING

LAMINATED OBJECT MANUFACTURING

Typical system of Laminated Object Manufacturing (LOM) has been shown in figure 5. It can be seen form the figure that the slices are cut in required contour from roll of material by using a 25-50 watt CO_2 laser beam. A new slice is bonded to previously deposited slice by using a hot roller, which activates a heat sensitive adhesive. Apart from the slice unwanted material is also hatched in rectangles to facilitate its later removal but remains in place during the build to act as supports. Once one slice is completed platform can be lowered and roll of material can be advanced by winding this excess onto a second roller until a fresh area of the sheet lies over the part. After completion of the part they are sealed with a urethane lacquer, silicone fluid or epoxy resin to prevent later distortion of the paper prototype through water absorption.

CASE STUDY

A project has been prepared at Gdansk University of Technology & medium sized industrial company in north Poland. Here Rapid Prototyping technique was applied and tested for a new pomp rotor construction. An interactive process of product development in North Poland Company occurs when errors are discovered and more efficient, better design solutions are looked for study of an earlier generation prototype of pomp rotors. Traditionally the main problems involves the series of advanced machining processor utilizing a variety of expansive tooling; it is time consuming and cost consuming. Manufacturing takes several months to prepare and the production of a single complicated part, as a pomp rotor, by conventional machining operations can be very difficult. These factors were the main reason to utilize stereolithography technology for pomp rotor manufacturing at Gdansk University of Technology.

FIGURE-6 THE POMP ROTOR PROTOTYPE USING RAPID PROTOTYPING TECHNOLOGY

Applications

RP technology has potential to reduce time required from conception to market up to 10-50 percent [1] (Chua and Leong, 2000). It has abilities of enhancing and improving product development while at the same time reducing costs due to major breakthrough in manufacturing. Therefore, RP technologies are successfully used by various industries like aerospace, automobile, jewelry, coin making, saddletrees etc. Its various applications are listed below-

1. In medical field –

- Rapid prototyping is used for diagnosis, surgery planning, training and for design and manufacture of the custom implants and also the model of skull.
- The 3D CAD(computer aided design) and CAM(computer aided manufacturing) is used for design and development of new products. It shortens the time to market and helps further in research.[5]
- The conversion of CT scan or MRI results which are taken as input and then converted in to CAD file then analyze those files with the help of CAM software then production that product with rapid prototyping.
- The Physical models enable correct identification of bone abnormality, intuitive understanding of the anatomical issues for a surgeon, implant designers and patients as well.[6]

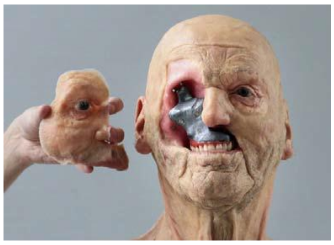
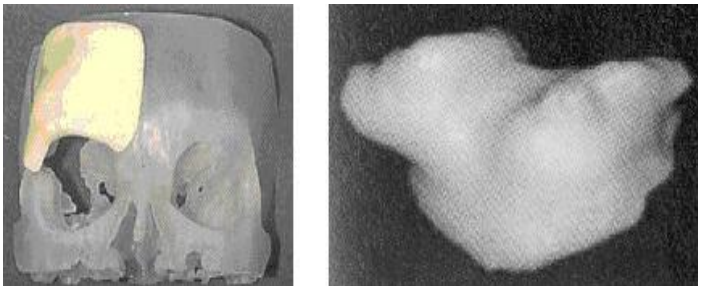


FIGURE-7 DAMAGED FACIAL SKULL REPLACED BY RP MODEL

2. In Mechanical Engineering- Analysis and Planning

- Rapid Prototyping is widely used to form and fit large mechanical models.
- It provides ease in the flow analysis and indentifying points of stress concentration.
- It is often used as a proof of concept and visualizing the object.
- Rapid Prototyping has wide applications in the Automobile and Aerospace Industry.



(a) SL model with resection template (b) Silicon implant molded from a tool

[1](after pham and demov, 2001)

FIGURE-8 MECHANICAL APPLICATIONS OF RP PROCESS

3. In Electrical appliances-

The house holding electrical appliances are widely manufactured in the PR techniques. These techniques are very useful for manufacturing the special contours in an electrical item.

4. In textile-

The RP techniques models are widely used in textile industries. The complicated contour profile dresses are designing in the 3D model with aid of computer and directly inter connected with manufacturing machine.

5. In Furniture Designing-

The furniture is designed and manufacturing with a aid of RP techniques. [7]This model has low weight and no temporary and permanent joints. It is made up of a single piece without any joints with different profiles.

6. In Foot-Ware Designing-

The foot-ware for a human comfort is manufacturing in RP technique. This type of foot-ware should have light weight and stronger than the conventional model. And also the complicated design of foot-ware is developed in the RP technique models without any fastener. The reliability is very high compared with conventional model.

7. Architectural Interior design-

An RP technique plays an important role in architectural interior design like stature, wall mountings and toys. [8] The RP model of interior decoration has good surface finishing and aesthetics.

8. It is also used in crafts, arts and Reverse Engineering applications, Short Production Runs and Rapid Tooling.

PART DEPOSITION PLAN

A defect less STL file is used as an input to RP software like Quick SIice or RP Tools for further processing. At this stage, designer has to take an important decision about the part deposition orientation. The part deposition orientation is important because part accuracy, surface quality, building time, amount of support structures and hence cost of the part is highly influenced [9] (Pandey et al., 2004b). In this section various factors influencing accuracy of RP parts and part deposition orientation are discussed.

1. Factors influencing accuracy

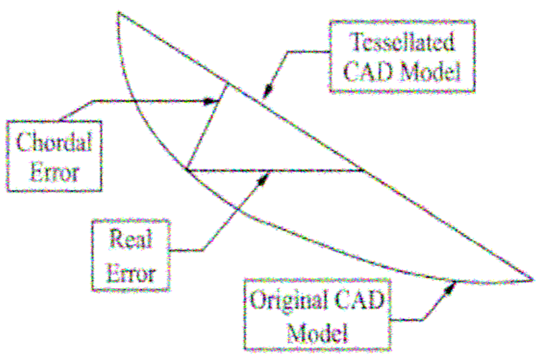
Accuracy of a model is influenced by the errors caused during tessellation and slicing at data preparation stage. Decision of the designer about part deposition orientation also affects accuracy of the model.

Errors due to tessellation: [2] In tessellation surfaces of a CAD model are approximated piecewise by using triangles. It is true that by reducing the size of the triangles, the deviation between the actual surfaces and approximated triangles can be reduced. In practice, resolution of the STL file is controlled by a parameter namely chordal error or facet deviation as shown previously. It has also been suggested that a curve with small radius (r) should be tessellated if its radius is below a threshold radius (ro) which can be considered as one tenth of the part size, to achieve a maximum chordal error of (r/ro) .

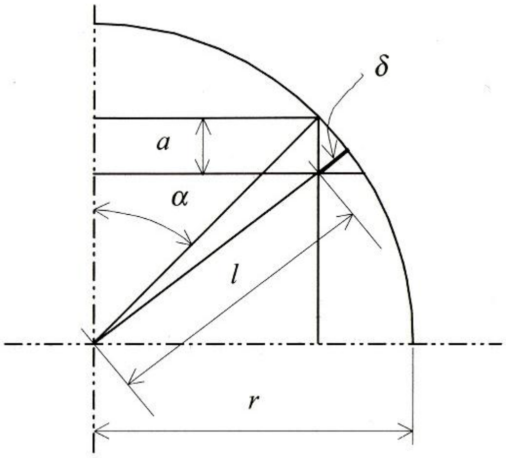
Errors due to slicing*:* Real error on slice plane is much more than that is felt, as shown in figure 9(a). For a spherical model Pham and Demov (2001) proposed that error due to the replacement of a circular arc with stair-steps can be defined as radius of the arc minus length up to the corresponding corner of the staircase, i.e., cusp height (figure 9(b)). Thus maximum error (cusp height) results along z direction and is equal to slice thickness. Therefore, cusp height approaches to maximum for surfaces, which are almost parallel with the x-y plane. Maximum value of cusp height is equal to slice thickness and can be reduced by reducing it; however this results in drastic improvement in part building time.
Therefore, by using slices of variable thicknesses (popularly known as adaptive slicing, as shown in figure 10), cusp height can be controlled below a certain value.

2. Part Building

During part deposition generally two types of errors are observed and are namely curing errors and control errors. Curing errors are due to over or under curing with respect to curing line and control errors are caused due to variation in layer thickness or scan position control. Figures 11 illustrate effect of over curing on part geometry and accuracy. Adjustment of chamber temperature and laser power is needed for proper curing. Calibration of the system becomes mandatory to minimize control errors. Shrinkage also causes dimensional inaccuracy and is taken care by choosing proper scaling in x, y and z directions. Polymers are also designed to have almost negligible shrinkage factors. In SL and SLS processes problem arises with downward facing layers as these layers do not have a layer underneath and are slightly thicker, which generate dimensional error. If proper care is not taken in setting temperatures, curling is frequently observed.



(a) Real error slice plane [10] (after Pandey et al., 2003a)



(b) Error due to replacement of arcs with stair-steps, cusp height [3]
(after pham and Demov, 2001)
Figure 9: slicing error

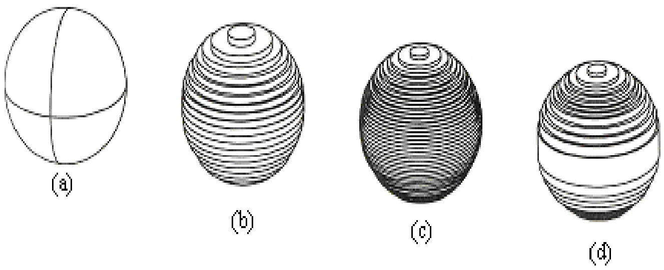
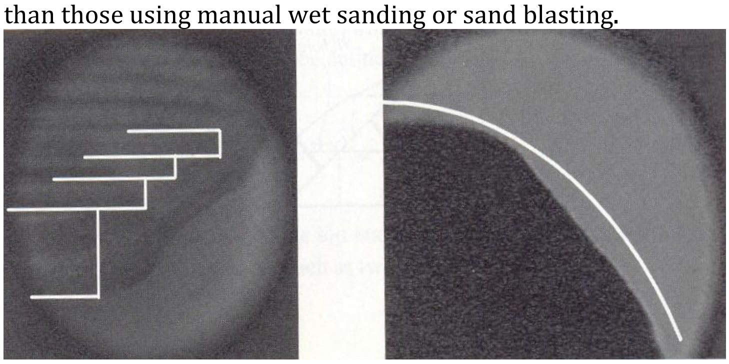


Figure 10: Slicing of a ball, (a) No slicing (b) Thick slicing (c) This slicing
(d) Adaptive slicing [3] (after Pham and Demov, 2001)

3. PART FINISHING

Poor surface quality of RP parts is a major limitation and is primarily due to staircase effect. Surface roughness can be controlled below a predefined threshold value by using an adaptive slicing [2](Pandey et al., 2003b). Further, the situation can be improved by finding out a part deposition orientation that gives minimum overall average part surface roughness [11](Singhal et al., 2005). However, some RP applications like exhibition models, tooling or master pattern for indirect tool production etc. require additional finishing to improve the surface appearance of the part. This is generally carried by sanding and polishing RP models which leads to change in the mathematical definitions of the various features of the model. The model accuracy is mainly influenced by two factors namely the varying amount of material removed by the finishing process and the finishing technique adopted. A skilled operator is required as the amount of material to be removed from different surfaces may be different and inaccuracies caused due to deposition can be brought down. A finishing technique selection is important because different processes have different degrees of dimensional control. For example models finished by employing milling will have less influence on accuracy than those using manual wet sanding or sand blasting.



(a) Thicker bottom layer (b) Deformed hole boundary
Figure 11: Over-curing effects on accuracy in Stereolithography
[3] (after Pham and Demov, 2001)

4. SELECTION OF PART DEPOSITION ORIENTATION

This is one of the crucial decisions taken before slicing the part and initiating the process of deposition for a particular RP process. This decision is important because it has potential to reduce part building time, amount of supports required, part quality in terms of surface finish or accuracy and cost as well. Selection of part deposition orientation is process specific where in designer and RP machine operators should consider number of different process specific constraints. This may be a difficult and time consuming task as designer has to trade-off among various conflicting objectives or process outcomes. For example better part surface quality can be obtained but it will lead to increase in the building time. [9]Pandey et al. (2004b) handled conflicting situation of the abovementioned two objectives and proposed use of multi-objective genetic algorithm for finding out optimum part deposition orientations (pareto optimal solutions) for FDM process. In their work, amount of support structures were also minimized implicitly. Thrimurthullu et al. (2004) converted multi-objective problem into single objective problem and then solved by using real coded genetic algorithm. [11] Singhal et al. (2005) made an attempt to find out optimum part deposition orientation for SL process by using optimization tool box of MATLAB 6.5 for minimizing overall part surface roughness. Except these, researchers suggested to find out a suitable part deposition orientation for objectives like maximum accuracy, minimum building time, support structure or cost. A thorough review of the various part deposition orientation studies has been done by [12] Pandey et al. (2004a). [3]Pham and Demov (2001) discussed guidelines for selection of part deposition orientation for SL and SLS processes.

CONCLUSION

Rapid Prototyping is one of the fastest growing technology in the world. It gives the mechanical engineer the possibility to visualize those complex shapes not easily seen or understood on connectional drawings, and touch them to verify the shape. It can be used in early design stages to build a conceptual model or in later stages when details are needed. This paper provides an overview of RP Technology and emphasizes on their ability to shorten the product design and development process and classification of a few RP processes used. An attempt has been made to include some important factors to be considered before starting part deposition for proper utilization of potentials of RP processes.
In a short time, rapid prototyping will become a technology that will be used routinely by many design engineers in conjunction with the traditional existing ways of creating scale models of mechanical parts.

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