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Rapid Prototyping Technology for New Product Development

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Abstract— *A Rapid prototyping (RP) is a production technology in which physical model of a computer model is manufactured without the need for any jig or fixture or without or with negligible human interaction. Rapid prototyping is also known as layer manufacturing, material deposit manufacturing, material addition manufacturing, solid freeform manufacturing and three-dimensional printing. In the last decade, a number of RP techniques have been developed.*

This paper is targeted towards the growth and trend of the technology, areas of applications of RP and its significant benefits to manufacturing industries. There are various components which are associated with RP. In this paper authors have reviewed various literatures available on this topic and have tried to prepare a very concise and progressive review. Manufacturing managers can refer this paper for the application of various important factors relating rapid prototyping.

Keywords: *Rapid Prototyping, Product Development, CAD, .STL (Standard Template Library) file*

I. INTRODUCTION

Due to the requirement of better quality of products and the pressing time constraints, the need for evaluating all feasible design alternatives with least cost and time is required for a sustainable product development in the current era. Computer aided design; manufacturing and analysis technologies provide a valuable resource tool for the futuristic design. Further recent advances in technologies like reverse engineering, rapid prototyping and tooling are increasingly enabling fast, inexpensive ways to create parts directly from computer aided design models. It is promising that if these technologies are given there due significance in the engineering curriculum the impact will be revolutionizing for the Indian industries.

Rapid prototyping is an automated process that quickly builds physical prototypes from 3D CAD files composed of surface quality or solid models [6]. Any manufacturing process can be classified as either subtractive, formative or additive. Every manufacturing process either falls completely into one of these categories, or is a hybrid process falling into more than one. In the manufacturing arena, productivity is achieved by guiding a product from concept to market quickly and inexpensively. Rapid prototyping technology aids this process. These processes produce objects by addition of material on a layer-by-layer basis while in case of conventional methods which do so by removal of materials.

Rapid prototyping develops in last few decades and these can be classified in different processes some of which are stereo lithography (SL), selective laser sintering (SLS), laminated object manufacturing (LOM), fused deposition model (FDM), direct shell production (DSP), 3D Printing. Using these technologies, manufacturing time for parts of virtually any complexity is measured in hours instead of days, weeks, or months; in other words, it is rapid. It is automatic manufacturing of a prototype part from a three-dimensional (3-D) CAD drawing. Rapid prototyping can be a quicker, more cost-effective means of building prototypes as opposed to conventional methods.

In RP the fabrication processes fall into three categories: subtractive, additive, and compressive [23]. In a subtractive process, a block of material is carved out to produce the desired shape. An additive process builds an object by joining particles or layers of raw material. A compressive process forces a semi-solid or liquid material into the desired shape which it is then induced to harden or solidify. Most conventional prototyping processes fall into the subtractive category & these machining methods can be used on parts with very small internal cavities or complex geometries easily and efficiently.

II. REASONS FOR RP

There are several reasons for implementing rapid prototyping in product development like rapid response to market demand and market changes, reduced manufacturing lead time, reduced cost of operation, customer satisfaction, improved business performance, minimize sustaining changes, increased product lifetime etc. A concise review about some of these factors is being explained as follow:

- Time and cost saving: The applications of the RP shows that the firms uses rapid prototyping technologies to achieve both cost and time savings in the process of new product development. In most cases firms using rapid prototyping have gained time reductions in the production of prototype tooling and parts, which is mostly how these time savings have been specified. The time reductions on prototyping vary greatly, ranging from 60 to 90% (In 1994, Pratt & Whitney). On the whole this range is likely to be realistic given that the estimation of time savings, when it is compared with the conventional methods of prototyping. Little information is provided in the public domain about cost savings. However it is clear that there is lots of potential for cost reduction. For example, if mistakes can be identified before commitments are made to expensive tooling, then the costs associated with modifying such tools can be avoided. However, the information on cost reductions should be treated with some caution where calculations or the assumptions have to be made.

- Innovation: It is evident from study that some firms are using rapid prototyping in more innovative ways than others [3]. These innovative applications are: the development of new analysis and testing procedures (for example, the Andersen Corp.); manufacture of production tooling (for example, the Buddy/L); improving communications across product divisions (for example, the Square D Company); and supporting customized manufacturing (for example, the Wright Medical Technologies). As the high capital costs of some rapid prototyping machines are very high, especially the larger ones, these innovative applications are probably the key to the successful and cost-effective use of the technologies. It may be the case that rapid prototyping will only be seen as financially viable when these wider potential benefits are taken into account.
- Reduced Waste: Unlike subtractive manufacturing, additive manufacturing (RP) does not leave unused cut-off stock or chippings. With additive manufacturing, model material is applied only where it is needed, although some processes require the use of a sacrificial supporting structure especially in the case of overhanging geometry.
- Rapid Prototyping decreases development time by allowing corrections to a product to be made early in the process (Halliday 1995). The RP gives engineering, manufacturing, marketing, and purchasing departments a look at the product early in the design process, so that the mistakes can be corrected and changes can be made while they are still inexpensive. The trends in manufacturing industries continue to emphasize the following which can be achieved by RP:
  - Increasing number of variants of products.
  - Increasing product complexity.
  - Increasing product lifetime.
  - Decreasing delivery time.

Rapid Prototyping improves product development by enabling better communication in a concurrent engineering environment. It extend product lifetime by adding necessary features and eliminating redundant features early in the design.

III. COMPONENTS: PHILOSOPHIES & TECHNIQUES

Rapid prototyping is a fabrication method whereby artifacts are constructed by depositing material layer by layer under computer control [4]. The basic methodology for all current rapid prototyping techniques can be summarized as follows:

- A CAD model is constructed, and then it is converted to STL format. The resolution of the process should be set to minimize stair stepping.
- The RP machines then processes the .STL file by taking it as input and create sliced layers of the model as output.
- The first layer of the physical model is created and then the model is lowered by the thickness of the next layer, and the process is repeated until completion of the model.
- Finally the model and any other supports are removed and the surface of the model is then finished and cleaned.

Generally the data flow and process of RP can be understood by the process flow chart given by Gebhardt (2003)

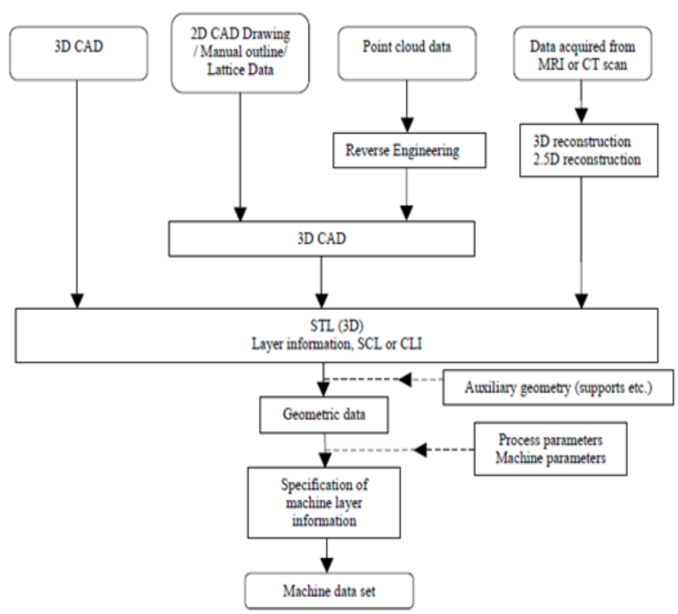

Fig.1. Generalized illustration of data flow in RP

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For deciding whether a process can be classified as a RP process or not, five criteria are specified by Burns (1993) which can be applied to any process to differentiate it from RP processes.

- The process should take in raw material in some shapeless form such as blocks, sheets or a fluid, and produce solid objects with a definite shape.
- The process must do this without a significant amount of human interaction.
- The process must produce shapes with some degree of three dimensional geometrical complexities. This criterion eliminates the forming of simple tubes or rods by extrusion and cutting or drilling of simple holes in sheet material.
- The process must not involve the manufacture of new tools for each different shape to be generated (part specific tooling). This criterion eliminates all types of molding and casting, EDM die sinking and copy milling.
- Each item produced must be a single object not an assembly of component parts thus eliminating joining operations such as gluing, welding and riveting.

Based on these important factors the manufacturing process can be classified as RP and some of these rapid prototyping philosophies are discussed below.

III.I Stereo Lithography

In Stereo Lithography, (The patent for SLA (US Patent 4575330) was awarded on March 11, 1986 and the technique was publicized in Hulla) a laser generates an ultraviolet beam which solidifies the surface areas of a photopolymer as per the instructions in .STL file. This process continues, slice by slice, until the system completes the part. 3D Systems offers three models of the SLA. The process begins with the vat filled with the photopolymer liquid and the elevator table set just below the surface of the liquid. The operator loads a three-dimensional CAD solid model file into the system. If needed, supports are designed to stabilize the part during building and post-curing. The translator converts the drawing into the .STL file. The control unit slices the model and supports into a series of cross sections from 0.001 to 0.07 mm. thick. The computer-controlled optical scanning system directs and focuses the laser beam so that it solidifies a two dimensional cross section on the surface of the photopolymer. The elevator table then drops enough to cover the solid polymer with another layer of the liquid. A leveling wiper moves across the surface of the polymer. The laser then draws the next layer. This process continues, building the part from the bottom up, until the system completes the product. The part is then raised out of the vat and cleaned of excess polymer. It then proceeds to the Post Curing Apparatus for the final cure. Scanning time depends on the geometry of the contours, hatch patterns, the speed of the laser, and the recoating time (i.e. the time taken to place a layer of photopolymer over the last solidified layer).

III.II Selective Laser Sintering

Carl Deckard developed SLS at the University of Texas at Austin in 1986. SLS is the process that employs a powdered material approach to rapid prototyping. The process begins with the deposition of a thin layer of powder, which is heated to just below its melting point. A laser selectively traces the surface of the powder and sinters the material together. This process continues layer by layer until a final product is complete.

The SLS process begins with the preparation of the process chamber, which is heated to the operating temperature. After that one powder feed piston distribute a layer of powdered material and simultaneously the part-building cylinder lowers to the desired layer thickness. The other powder feed piston also lowers to accommodate any surplus material, which the leveling roller transfers across the build area. The deposited powder is then heated to a temperature which is just below its melting point with the laser which is guided with the help of a raster scanning pattern. The un-sintered powder remains to support the next layer, which is then distributed, leveled, and sintered.

This method differs from the SLA as mentioned above where there is only one phase transition, and in the SLS there are two phase transition, first from solid to fluid & second back to solid again. The materials being used or investigated in this process include plastics, wax, metals, and coated ceramics. An advantage to this system is its ability to provide supported building as the un-sintered powder surrounding the part in the build cylinder which acts as a natural support for the next layer so no extra supports need to be built such as in some photopolymer systems. Also, the excess powder material can be returned to the powder feed cartridges which is then reused.

III.III Laminated Object Manufacturing

Laminated Object Manufacturing (LOM) is a system developed in 1989 by Helisys, Inc., Torrance, CA. LOM differs from the systems discussed above. In SLA & SLS the parts are building up by adding materials to a stack through a forming process, and in LOM layers of sheet materials such as paper, plastics, or composites are attached to a stack, and the laser cuts away the unused portions.

In the LOM the process starts with a winding and an unwinding roll which provides ribbon of the material to the machine and a stepper motor positions the material onto the building platform. Then a heated roller moves across the surface of the material & bonds it to the stack which is then cut to the required profile by focusing the CO_2 laser beam. The beam is guided on the x-y positioning table which consists of sensors, mirrors and optics reflectors. The area of material surrounding the part profile is cut in a crosshatch pattern to facilitate its removal later. The excess material which is left in the building block acts as a support structure for the next layer.

This process is considerably fast as the laser is cutting around the periphery of the object, building a thick-walled part rather than thin-walled one. One of the great advantages with this process is that it is not limited by the complexity of the part. Also in LOM there are virtually no internal stresses so the parts have no deformation or shrinkage commonly associated with other photopolymer systems.

III.IV Solid Ground Curing

The SGC method was developed and commercialized by Cubital Ltd. (Israel). In this system the input of the three-dimensional CAD data of the part is used to generate the cross-sectional slice data of the model and for selection of layer thickness. The production machine then uses these data to cure an entire layer of photopolymer in a solid environment. An ultraviolet light completely cures the material through a photo mask & no post curing is required.

In the starting of this system an image representing the cross- sectional layer is sent to the mask plotter. Then the mask plotter generates the negative image of the layer with the help of a glass plate which is charged with ions and an electrostatic toner. At that time, the work piece carriage is present at the resin application station. Then the carriage and mask plotter meet at the exposure cell, where a shutter opens for 3 seconds and explode the resin to ultraviolet light through the transparent areas of the mask plotter. Then all the exposed areas are completely cured and the mask plotter moves back to the plotting station where it is physically and electrostatically erased and prepared for the next layer. In that mean time the part is again exposed to ultraviolet light without the mask plotter. This solidifies the residual resin that the wiper could not pick up. Then the carriage moves to the wax applicator station, which deposits a layer of wax 0.2 mm thick to fill in all voids and cavities if any & the wax is then solidified by a cold plate at the cooling station.

The work piece then moves to the milling station where a fly cutter mills the layer down to the desired thickness & a vacuum collects the chips produced during this process. Then work piece carriage lowers to accommodate the spreading of resin for the next layer, and the process continues until the part is complete. At last the water-soluble wax is melted in a microwave oven, and the part is cleaned in warm water. This method cures each layer separately as it is built.

This minimizes shrinkage eliminates the need for post-curing. Also, the solid polymer and wax environment eliminates the need for elaborate support structures. This process can build parts of geometric complexity with ease. But the problem with this method is that it produces a lot of material waste. The resin picked up by the wiper and vacuum during the milling process cannot be used again as uncured resin is hazardous material.

III.V Fused Deposition Modeling

FDM begins with a software process which processes an STL file (Stereolithography file format), mathematically for slicing and orienting the model which is required to initiate the building process. Also the support structures can be generated if required. The machine may dispense multiple materials to achieve different goals: For example, one material may build up the model and another may be used as a soluble support structure. For another example, multiple colors of the same type of thermoplastic may be laid down on the same model.

In the process first of all the thermoplastics are heated past their glass transition temperature. Then the thermoplastics are deposited by an extrusion head, which follows a tool-path defined by CAM software, and the part is built from the bottom to the up, layer by layer & one layer at a time. A plastic filament or metal wire is unwound from the coil and it supplies the material to an extrusion nozzle which can turn the flow on and off. The nozzle is heated to melt the material and can be moved in both horizontal and vertical directions by a numerically controlled mechanism, directly controlled by a computer-aided manufacturing (CAM) software package. The model or part is produced by extruding small beads of thermoplastic material to form layers as the material hardens immediately after extrusion from the nozzle. Stepper motors or servo motors are typically employed to move the extrusion head. Although as a printing technology FDM is very flexible, and it is capable of dealing with small overhangs by the support from lower layers, but generally it has some restrictions on the slope of the overhang.

III.VI Three Dimension Printing

3D printing (The patent for 3DP (US Patent 5204055) was awarded on April 20, 1993, but the work was reported earlier in Sachs et al) is a process of making a three-dimensional solid object of virtually any shape from a digital model. 3D printing is achieved using an additive process, where successive layers of material are laid down in different shapes. 3D printing is also considered distinct from traditional machining techniques, which mostly rely on the removal of material by methods such as cutting or drilling (subtractive processes). To perform a print, the machine reads the design from a .STL file and lays down successive layers of liquid, powder, paper or sheet material to build the model from a series of cross sections. These layers, which correspond to the virtual cross sections from the CAD model, are joined or automatically fused to create the final shape. The primary advantage of this technique is its ability to create almost any shape or geometric feature.

The various RP technologies have their own advantages and limitations over one another and the selection between different techniques depends upon the need of manufacturer. Depending upon the requirements and benefits of the manufacturer the suitable technique can be selected after comparing all the available RP techniques

IV. RESEARCHES IN THE AREA OF RP

Rapid prototyping concept is relatively new and it initiate in late 1980s and early 1990s. With the introduction of the first rapid prototyping system in 1987, certain forward thinking manufacturers immediately realized the potential of this new technology to dramatically reduce their product development cycles (Jacobs, 1992) & many of the researchers starts working on this field.

Pham & Dimov (1998) discussed the process for selecting the part deposition orientation for SLA and SLS processes and similar work was expended by Pandey et al. (2003) in which a brief review about the part deposition orientation was made by them. Yang et al. (1999) integrate a CAD system with MRP (Manufacturing Resource Planning) system based on STEP protocol. This reduces the design choice impact on required materials. However there work did not completely address the integration problem between the product design and process planning, and between processes planning and shop floor scheduling which is very critical problem associated with RP. Howard et al. (1998) have proposed a generic manufacturing planning and control system architecture for different manufacturing environments in their work however; this work was not concerned with the involved product design tasks.

Frank and Fadel (1994) developed a rule-based system that uses the tessellated CAD model of the part as input and two geometrical features (hole, surface of revolution, round, thin feature, plane, free-form surface or overhang) are chosen by the user and the system suggests an orientation from these two features based on surface finish, supports and trapped volumes. The rules were obtained by consultation with experts. Cheng et al. (1995) describe a system which works directly on the CAD model and suggests an orientation by first maximizing the surface smoothness and then minimizing the build time. Jamieson and Hacker (1995) have insisted that 3D CAD models are needed for rapidly prototyping the components. They have also presented a methodology for developing an adaptive slicer from the commercial CAD system. Luo (2004) implement adaptive slicing algorithm for rapid prototyping (RP) processes, this approach determines the layer thickness based on comparing the contour circumference or the center of gravity of the contour with those of the adjacent layer also Taguchi method was used to analyze the process parameters for the proposed RP system to improve the quality of the RP part. Jain & Kuthe (2013) studied the feasibility of manufacturing industry using rapid prototyping (FDM Approach) and compared the result with sand casting. They use the software named “AUTOCAST-X” for designing and simulating zero defect casting. SEVIDOVA et al (2008) formulate the influence of different coatings on the surface strength of RP products using composite material. The influence of different materials like Ni, Cr, Ni + TiN coating, Cu–Ni–Cr +TiN coating on surface hardness and wear resistance on RP products obtained by the SLS method from powder materials was briefly studied. Byun & Lee (2004) deals with the selection of an optimal RP system that best suits the end use of a part by using multiple attribute decision making (MADM) and TOPSIS. Their study include only the major attributes that significantly affect the performance of an RP system such as accuracy, roughness, strength, elongation, part cost and build time. The modified TOPSIS approach was also proposed to analyze both quantitative and qualitative data. This method determined the ranks between the RP systems and effectively reflected the information produced for the decision using the multiple attributes. The ranks were then altered using the weights assigned by a pairwise comparison matrix to provide the final ranking. The results of this study help us in selecting the most suitable RP process to fabricate a complex part that contains many features of differing sizes. Phillip son (1997) suggested the selection of RP process based on multi criteria optimization method by selecting cost, quality and time as major factors. Whereas Muller & Bauer (1996) uses the benefit value analysis method based on computer analysis to calculate build time and hourly rate which is then used for selecting & ranking different RP process.

V. APPLICATION OF RP

Rapid prototyping have very wide area of applications and it is the future of all the manufacturing industries. However it is mainly used in Modeling, Product Design and Development, Reverse Engineering applications, Short Production Runs and Rapid Tooling. RPT is also used in medical field, to make exact models resembling the actual parts of a person, through computer scanned data, which can be used to perform trial surgeries, RP techniques are also used to make custom-fit masks that reduce scarring on burn victims. SLS have been used to produce superior socket knees. Very tiny, miniature parts can be made by electrochemical fabrication, and also in jewelry designs, crafts and arts. PR is being used successfully.

VI. DISCUSSIONS & CONCLUDING REMARKS

The RPT is still in developing stage and a lot of work can be done to improve as it can lead to substantial reduction in build-up time & can satisfy the market needs. Some of the possible advancements are discussed in this paper.

The improvement in laser optics and motor control system can improve the accuracy of RPT as it has lots of possibilities. Also this helps in reducing the processing time and increasing the speed of response. There are possibilities of developing the new materials and polymers so that they are less prone to curing and temperature induced warp ages which can further improve the processes. However the development in the introduction of non-polymeric materials including metals, ceramics, composites, and powder metallurgy in RPT can further increase the range of rapid prototyping. However replacing the material by steel or composites is still not easy and people fear for its implications. Currently, the size is also a very big restriction, so the capability for larger parts can be expected in the near future. Also, the demand now is low and with further advancement of this technology the demand will increase. The demand can also be improved with proper awareness and training about the RPT. The advancement in computing systems and viability to support net designs from a distant country which can be feed directly on the RP machines for manufacturing is also a new possibility.

RP companies usually limit the marketing efforts and industry awareness; hence most engineering and manufacturing professionals are not fully aware of the RP potentials which leads to unfamiliarity with the application of RPT and its complete adaptability and how exactly this new and advanced technology will be of helpful is still not known. Also due to high equipment cost, very few organizations can invest in these new machines. Currently, RPT is bounded to modeling, specimen making and designing. So at last we can conclude that there is lots of potential present in RP and lots of future work can be done to improve RPT.

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