Rapid Prototyping:
Theory and Practice

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Rapid Prototyping:
Theory and Practice

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Preface

The current marketplace is undergoing an accelerated pace of change that challenges companies to innovate new techniques to rapidly respond to the ever-changing global environment. A country's economy is highly dependent on the development of new products that are innovative with shorter development time. Organizations now fail or succeed based upon their ability to respond quickly to changing customer demands and to utilize new innovative technologies. In this environment, the advantage goes to the firm that can offer greater varieties of new products with higher performance and greater overall appeal.

At the center of this environment is a new generation of customers. These customers have forced organizations to look for new methods and techniques to improve their business processes and speed up the product development cycle. As the direct result of this, the industry is required to apply new engineering philosophy such as ***Rapid Response to Manufacturing*** (RRM). RRM concept uses the knowledge of previously designed products in support of developing new products.

The RRM environment is developed by integrating technologies such as feature-based CAD modeling, knowledge-based engineering for integrated product and process design and direct manufacturing concepts. Product modeling within RRM requires advanced CAD technology to support comprehensive knowledge regarding the design and fabrication of a product. This knowledge-intensive environment utilizes knowledge-based technologies to provide a decision support utility throughout the design life cycle. Direct manufacturing uses rapid prototyping, tooling and manufacturing technologies to quickly verify the design and fabricate the part.

Rapid Prototyping (RP) is a technique for direct conversion of three dimensional CAD data into a physical prototype. RP allows for automatic construction of physical models and has been used to significantly reduce the time for the product development cycle and to improve the final quality of the designed product. Before the application of RP, computer numerically controlled (CNC) equipments were used to create prototypes either directly or indirectly using CAD data. CNC process consists of the removal of material in order to achieve the final shape of the part and it is in contrast to the RP operation since models are built by adding material layers after layers until the whole part is constructed. In RP process, thin-horizontal-cross sections are used to transform materials into physical prototypes. Steps in RP process are illustrated in Figure 1.

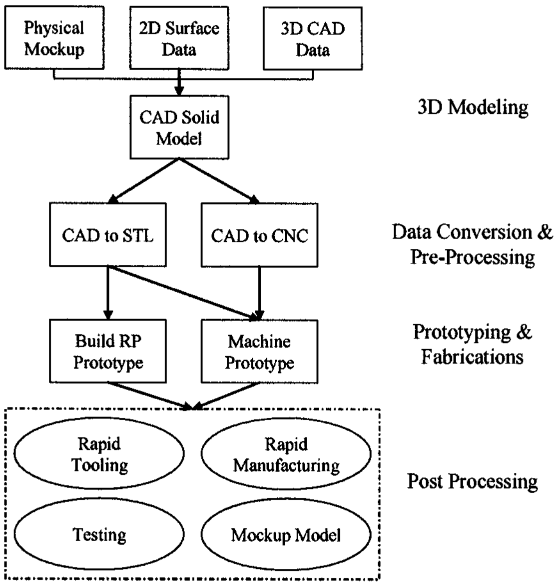

Figure 1. Generic RP Process

Depending on the quality of the final prototype, several iterated is possible until an acceptable model is built. In this process, CAD data is interpreted into the Stereolithugraphy data format. Stereolithugraphy or "stl" is the standard data format used by most RP machines. By using "stl", the surface of the solid is approximated using triangular facets with a normal vector pointing away from the surface in the solid. An example of triangulated surface using the stl format is illustrated in Figure 2.

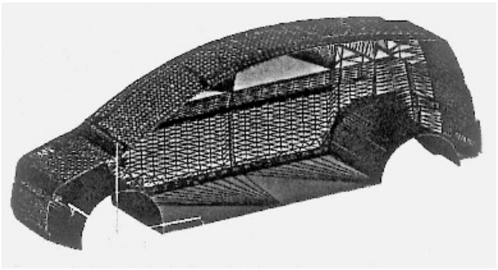

Figure 2. Triangulated surface

Since chordal deviation is used to approximate real mathematical surface, it is important to minimize this deviation to better approximate the real surface. This impact the size of the required triangles and it will also increase the processing time. Figure 3 illustrate the stages of product development using RP technologies.

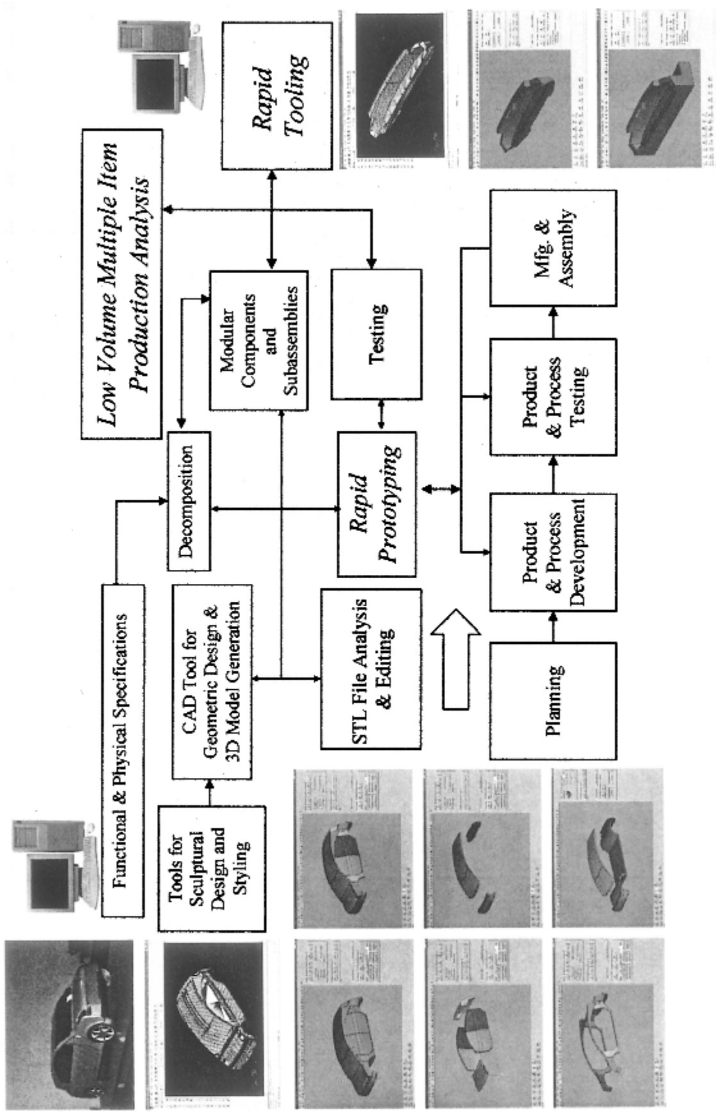

Figure 3. Integrated RP and Product Development Cycle

A wide range of technologies are developed to transform different materials into physical parts. For RP process, materials are categorized into liquid, solid and powdered. A process that has been widely used by many industries is the SLA or Stereolithography Apparatus RP Process. SLA is a liquid-based process. The material vat is part of the machine and is only removed if the liquid resin replaced. The SLA process uses the Ultraviolet laser beams to solidify the liquid polymer as it traces each layer. The part and the support are built simultaneously. The finished part is then manually removed, cleaned and finally post-cured using ultraviolet chamber. Another known process is the Fused Deposition Modeling or FDM. FDM is a solid-based process. The build material is melted inside an extrusion head where the temperature is contorted based on the type of the material used (ABS, wax, etc.). This semi-liquid material is then extruded and deposited layer-by-layer. The finished part is then manually removed and cleaned. Selective Laser Sintering (SLS) is a powder-based process. A $C0_2$ laser is raster scanned across the surface of the powder, melting and bonding the power together. In this process the part is built inside the powered material which can then be brushed off and reused. Sample parts are illustrated in Figure 4.

Figure 4. Sample RP parts

As Rapid Prototyping (RP) technology becomes more mature, it is beginning to lend itself to other applications such as rapid tooling and rapid manufacturing. Some traditional tool making methods are considering the use of RP technologies to directly or indirectly fabricate tools. The Indirect method of rapid tooling (RT) uses the RP pattern as mold. This is considered as a good alternative to the traditional mold making since it is more efficient and requires less lead-time. This approach is also less expensive and allows for quick validation of designs. In direct RT method, the RP process is used for direct fabrication of the tools. In summary, rapid tooling is described as a process which uses an RP model as:

1. A pattern to create mold quickly (e.g. sand casting),

2. Copy an RP form into a metal (e.g. investment casting), and
3. Uses the RP process directly to fabricate a limited volume of tools.

The next natural evolution of RP technology is Rapid Manufacturing (RM). RM is the automated fabrication of products directly from CAD digital data. RM methods are categorized into the following three categories:

1. *One-Time Use Parts*
    - Resemble the minimum required functionality of the final part.
    - Developed in batch-size of one and used for short duration.
    - High Cost.
2. *Individually Customized Parts*
    - Developed in batch-size of one for an indefinite period of time.
    - Durability of the parts is an issue and is based on the material used and its properties.
    - High Cost.
3. *Multiple Item Production Runs*
    - Methods for rapidly manufacture low volume production runs.
    - Not economically efficient to create mass quantities of identical parts using rapid manufacturing

In summary, various RP, RT and RM solutions are available and it is difficult for any organization to know which one is the most appropriate. It is recommended that companies compare and investigate advantages and disadvantages for all available methods and then select the one that is most suitable for their operational needs.

The purpose of this edited book is to provide a comprehensive collection of the latest research and technical work in the area of Rapid Prototyping, rapid tooling and rapid manufacturing. This book is developed to serve as a resource for researcher and practitioners. It can also be used as a text book for advanced graduate studies in product design, development and manufacturing. In chapter 1, Kridle gives an introduction to structure and properties of engineering materials, testing methods used to determine mechanical properties, and techniques that can be used to select materials for rapid prototyping. In chapter 2, Abouel Nasr and Kamrani will introduce a new methodology for feature extraction and information communication using IGES data. In chapter 3, Lim and Zein will introduce DICOM (Digital Imaging and Communications in Medicine) data format. DICOM is becoming a global information standard that is being used by virtually every medical profession that utilizes images within healthcare industry. Automatic feature recognition from CAD solid systems highly impacts the level of integration. Non contact-based reverse engineering is discussed in chapter 4 by Creehan and Binanda. In chapter 5, Desai and Binanda present the contacted-based reverse engineering process. In chapter 6 Kim and Nnaji present a discussion on virtual assembly. This chapter will discuss how assembly operation analysis can be embedded into a service-oriented collaborative assembly design environment and how the integrated process can help a designer to quickly select robust assembly design and process for rapid manufacturing. A new innovative RP process is presented by Frank in chapter 7. A description of how CNC milling can be used for rapid prototyping is presented in this chapter. The proposed methodology uses a layer–based approach for machining for automatic machining of common manufactured part geometries. Khoshnevis and Asiabanpour will introduce the SIS process in chapter 8. The Selective Inhibition of Sintering or SIS process is a new RP method that, like many other RP processes, builds parts in a layer-by-layer fabrication basis. The process works by joining powder particles through sintering in the part's body, and by sintering inhibition at the part boundary. In Chapter 9, Khoshnevis and Hwoang present Contour Crafting. CC is a mega scale fabrication technology based on Layered Manufacturing process (LM). This fabrication technique is capable of utilizing various types of materials to produce parts with high surface quality at high fabrication speed. Method for strategic justification of RP technologies is presented in chapter 10 by Narian and Sarkis. Wilson and Rosen give a discussion on a method for selection of a RM technology under the geometric uncertainty inherent to mass customization. This topic is presented in chapter 11. Specifically, they define the types of uncertainty inherent to RM, propose a method to account for this uncertainty in a selection process and propose a method to select a technology under uncertainty. In chapter 12, Gad El Mola and Parsaei present a methodology for selecting the best RP solution technique using Analytical Hierarchy Process (AHP).

Ali K. Kamrani, Ph.D.

To Sonia and Arshya

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Chapter 1

Material Properties and Characterization

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Abstract:

As the name indicates, rapid prototyping (RP) has traditionally been used to provide a physical representation of a product in a relatively short time. RP is performed by either material removal or material addition. In material-removal type RP processes, the part is produce by machining it is out of a block of material; mainly using computer numeric controlled (CNC) machining centers. In material-addition type RP, the prototype is made by adding layers of materials using one of the available RP technologies.

Earlier prototyping materials and technologies were used to provide product designers with the ability to visualize the product, but with limited ability to assess the functional performance of the product. Nonetheless, prototyped parts also need to allow for design validation (assessment of the mechanical and physical behaviors); which indicates that the prototyping material should have the same characteristics as the production material. This was only available in limited situations where the prototyped parts were made using removal processes, casting processes, or metal spray deposition. However, recent advances in rapid prototyping technologies have

allowed the use of production type polymers that can be used to assess the functional behavior of these materials.
One of the shortcomings of testing prototyped products made of production type materials is that the material structure and the mechanical response of the prototyped part may not match those resulting from conventional processing (forming, molding, etc.) that is used to fabricate the actual product. This is caused by differences in processing conditions between RP and conventional processing. For example, if metal spray deposition is used for rapid prototyping purposes, the microstructure and level of porosity in the prototyped part are likely to be different from those of a cast or stamped product of the same size and shape.
Therefore, the goal of this chapter is to provide an introduction to structure and properties of engineering materials, testing methods used to determine mechanical properties, and techniques that can be used to select materials for material-addition type rapid prototyping.

Key words:
Mechanical Properties, Mechanical Testing, Material Selection, Polymers

1.1 Structural Properties of Materials

The structure of materials affects their properties and service behavior. Based on their structure, materials can be classified as either crystalline or non-crystalline (or amorphous)[1]. **Crystalline structures** are organized structures in which atoms and molecules of solids arrange themselves in a regular and repeating manner that is called ***lattice***. On the other hand, **amorphous structures** have some level of local order relative to their neighbors, but globally, they do not have an ordered structure like crystalline materials. Another difference between the two types of materials is related to their different thermal expansion behavior; this will be explained in more detail in sections 1.2.1 and 1.2.2.

1.1.1 Crystalline Structures

The lattice structure in a crystalline material is made up of a repeating order of atoms that is known as the ***unit cell***. Common types of unit cells that are observed in metals include body-centered cubic (BCC), face-centered cubic (FCC), and hexagonal close packed (HCP). Figure 1-1 shows a schematic of the atom arrangement in each of these three aforementioned