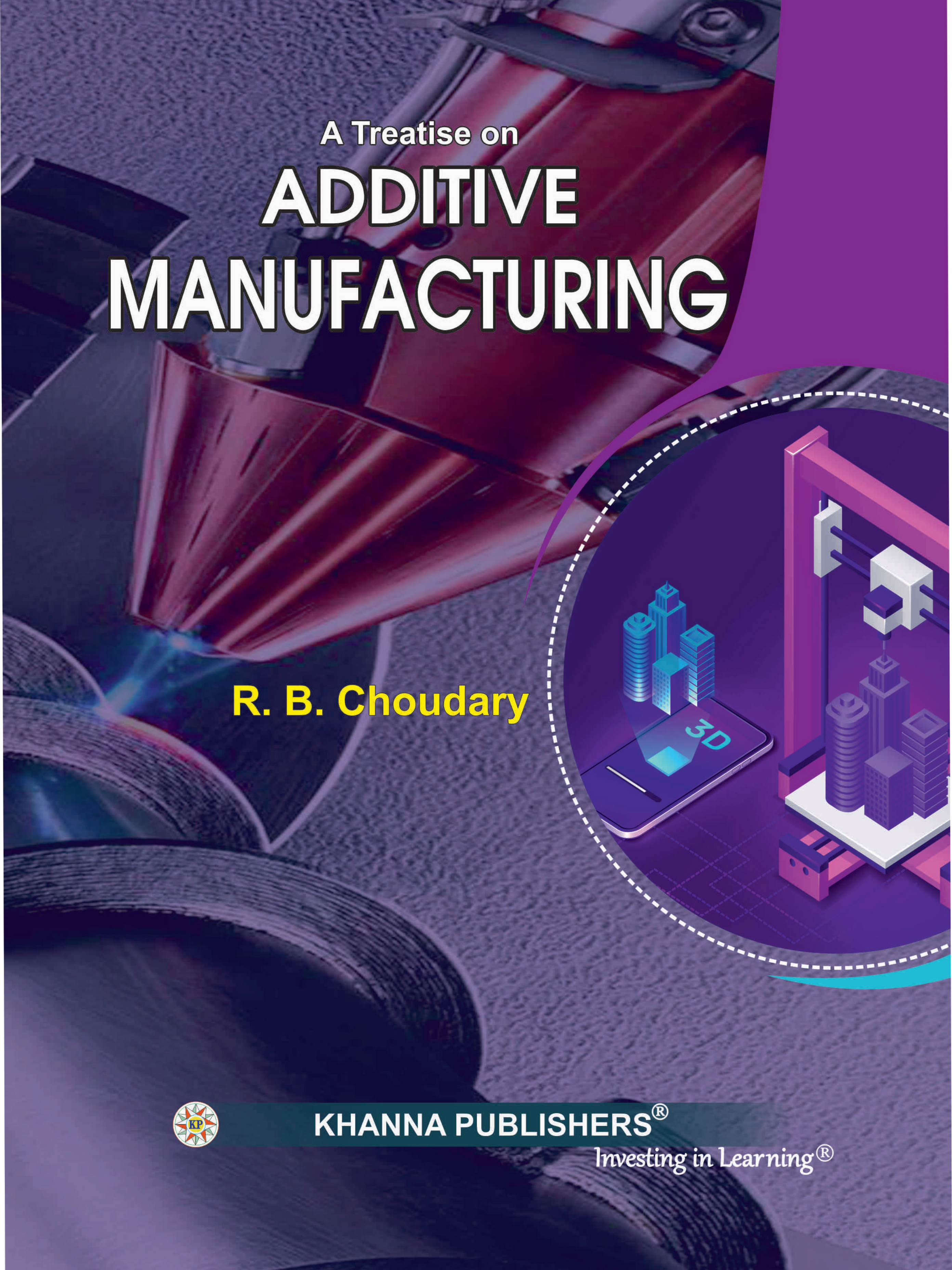

A Treatise on

ADDITIVE MANUFACTURING

R. B. Choudary

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A TREATISE ON

ADDITIVE MANUFACTURING

As per
National Education Policy-2020 and
Outcome Based Education

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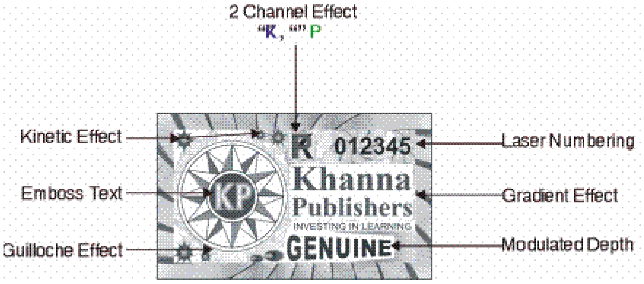

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Preface

Additive Manufacturing (AM) is a term that embraces rapid manufacturing and rapid tooling (RT). AM is an exciting new technology for quickly creating physical models and functional prototypes directly from CAD models. RT generally concerns the production of tooling using inserts. AM and RT are means for reducing the time-to-market of products.

This concise book is an abridged version of AM textbooks and research articles. It is expected to be very much helpful for beginners. I take this opportunity to acknowledge my indebtedness to authors and publishers of these books. Numerous materials available in the web on the subject were referred during the preparation of the book. The author is highly indebted to the eminent authors and their publishers whose works have been referred.

The lack of a simple book prompted the author to prepare this present work. The author does not pretend claim any originality for the material. He does not pretend claim a humble attempt in the presentation and in his efforts to combine good features of previous works in this field. The sources are appropriately acknowledged.

This book is intended to help the UG students in learning basics of AM. The first three chapters of this book describe the principles, processes, characteristics, capabilities, advantages, limitations and applications of the main known AM processes. Chapter 1 introduces the fundamentals of rapid prototyping, history of AM and discusses basics of AM. Then an overview of liquid based AM techniques, such as SLA and SGC, is presented. Chapter 2 provides an overview of solid based AM such as LOM, FDM and SDL. Chapter 3 deals with powder based AM techniques, such as SLS, 3DP, LENS, EBFFF and EBM. Indirect and direct methods of producing soft tooling, firm tooling (or bridge tooling) and hard tooling based on AM are dealt with in Chapter 4. Chapter 5 covers AM data formats and software used in AM the last chapter discusses AM applications in various industries.

R.B. Choudary

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1

CHAPTER

Introduction

Additive Manufacturing (AM) is a process in which digital 3D design data is used to make a component by depositing material layer by layer. AM includes a group of unique manufacturing processes developed to produce engineering prototypes with minimum lead time using a CAD model of the object. It is also called Rapid Prototyping (RP).

1.1. PROTOTYPE

A prototype is a sample, model or early version of a product. It is designed to test a concept or a process or to act as a piece to replicate or learn. It is a word used in a range of contexts. They include semantics, design, electronics and software programming. A prototype is typically used to evaluate a new design by users. Prototyping helps create specifications for a real and operational system rather than a theoretical one. In some design workflow models, creating a prototype is the step between formalizing and evaluating an idea. Fig. 1.1 shows a thermal model of a piston and crankshaft assembly presenting the temperature distribution.

Fig. 1.1 Thermal model of a piston and crank shaft assembly.

1.1.1. Three Phases of Development Leading to Rapid Prototyping

Prototyping or making models in the conventional way is an old-age exercise. The purpose of developing a physical prototype is to understand the conceptualization of a project. Therefore, a prototype is generally necessary prior to beginning of complete manufacture of the part. Prototype manufacturing is practised in several methods: removal of material, casting, molding, assembly with adhesives, etc. and with many types of materials like zinc, aluminum, wood, urethanes, etc. Prototyping methods have progressed through three phases of improvement, the last two of which have only come out in the recent 20 years. Similar to the process of modelling in computer graphics, the prototyping of physical models progresses into its third phase.

(*i*) **First phase:** *Manual prototyping* – Prototyping began as soon as people started to improve tools to help them live. But, prototyping applied to products in what is considered the first phase of prototype development began centuries back. In this first phase, the prototypes are generally not very refined and the manufacturing of the prototypes takes on an average around four weeks, based on the extent of intricacy and representativeness. The methods utilized to make these prototypes incline to be artisanal and are generally highly laborious.

(*ii*) **Second phase:** *Software or virtual prototyping* – As CAD/CAE/CAM applications developed more, the early 1980s saw the evolution of the second phase of prototyping – virtual or software prototyping. *Virtual prototyping* takes on new meaning as more and more computer tools become accessible: Computer models can now be stressed, tested, analyzed and modified as if they were physical prototypes. For instance, stress and strain analysis can be correctly estimated on the product with the ability to specify exact features and properties of materials. With such computer-based tools, multiple iterations of designs can be simply performed by changing the parameters of the computer simulations.

In addition, products and, as such, prototypes incline to get relatively further complex. As a result, the time taken to make the physical model inclines to increase dramatically up to around 4 months, as building physical prototypes yet depends on craft-based techniques, although the introduction of better precision machines like CNC machines helps.

Even with the arrival of rapid prototyping in the third phase, there is still strong support for virtual prototyping. Lee argues that there are still inevitable limitations with rapid prototyping. These consist of material limitations (either due to expense or due to the use of diverse materials than the proposed component), the inability to run endless simulation scenarios, and the likelihood that few or no reliable data can be collected from the rapid prototype to conduct finite element analysis (FEA). Specifically in the application of kinematic/dynamic analysis, he described a program that can assign the physical properties of many diverse materials, such as ice, steel, clay, plastic or any other custom material imaginable and conduct kinematic and motion analysis as if a working prototype existed. In spite of such strengths of virtual prototyping, there is an innate weakness that such soft prototypes cannot be inspected for phenomena that are not expected or accounted for in the computer program. As such, there is no assurance that the virtual prototype will be truly trouble free.

(*iii*) **Third phase:** *Rapid prototyping* – of physical parts, or else known as solid free-form manufacturing or desktop manufacturing or diaper manufacturing technology, represents the third phase in the development of prototyping. The invention of this sequence of rapid prototyping techniques is called as a "breakthrough" due to the huge savings in time, especially for complex parts. Although the parts (individual parts) are comparatively three times as complex as parts made in the 1970s, the time necessary to make such a component is now on average only three weeks. Since 1988, more than twenty diverse rapid prototyping methods have materialized.

1.1.2. Classification of Prototypes

Based on different aspects of a proposed design under study, prototypes are categorized as follows:

A *Proof-of-Principle* prototype aids to validate some important functional aspects of the proposed design, but typically does not have all of the functionality of the ultimate product.

A *Working Prototype* characterizes all or almost all of the functionality of the end product.

A *Visual Prototype* characterizes the dimension and look, but not the functionality, of the intended design.

A *Shape Study Prototype* is an early stage visual prototype in which the geometrical topographies of a design are stressed, with less concern for color, texture or other features of the final look.

A *Functional Prototype* captures both the function and appearance of the intended design, although it can be made with dissimilar methods and even an altered scale than the final design.

A *Paper Prototype* is a printed or hand-drawn representation of the user interface of a software product. These prototypes are normally used for the first tests of a software design and can be part of a software procedure to confirm design decisions before more expensive levels of design effort are used.

Demo Prototype: A small, crude version of a work such as a song, show, visual design, game or commercial application.

Evolutionary Prototype: A prototype that spans a substantial period of time and characterizes an upcoming version of a product. For example, a concept space craft developed as a potential future production model.

Form Study Prototype: An article or simulation that explores size, shape, form and appearance.

Functional Prototype A prototype that is near to the end product in functionality. For example, a user interface that works with test data but is not accurately developed as a well-designed, integrated system.

Minimum Viable Product: A product complete enough to be presented to customers as a market research tool or in beta version.

Mock-up Prototype: A general category of prototype that appears like the finished product but is totally missing in functionality. For example, a web page represented as an image or an automobile without an engine for use in wind tunnel testing. Fig. 1.2 shows a stereolithographic model of a camera with a balsa wood handle.

Fig. 1.2. Stereolithography mock-up of a camera with Balsa wood grip.

Paper Prototypes: Illustrations and basic cardboard models of design ideas.

Proof of Concept: Execution of a technique or design to show that it can work.

Proof of Principle: A test of a central idea.

Scale Model: A smaller, generally non-functional model. Generally used for huge items such as buildings, automobiles or aeroplanes.

Simulations: Software visualizations of physical things.

Static Prototype: A prototype that seems functional but is in fact hard-coded. For example, software that fakes with its data as opposed to integrating with data repositories.

Throwaway Prototype: A low cost prototype which is rapidly developed with limited quality and functionality. It is essentially the opposite of an evolutionary prototype which represents cutting edge design.

1.1.3. Evolutionary vs. Throwaway Prototypes

An *evolutionary prototype* is a full-bodied prototype that is persistently refined to characterize a product change, forthcoming product or advanced demonstration. This is usually a costly investment that is common in industries such as the automotive industry, which require products to be extremely refined before they hit the market. Fig. 1.3 shows an evolutionary prototype of a railway engine.

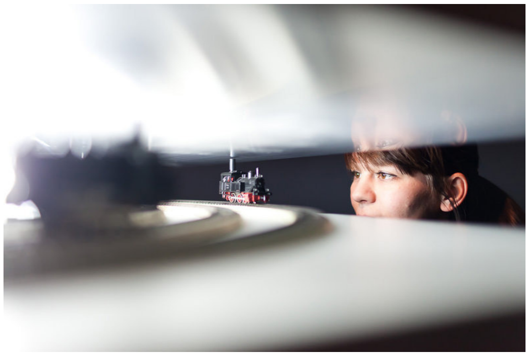

Fig.1.3. Prototype of a train engine

A throwaway prototype is a quick and inexpensive prototype designed to model an idea or feature. It is commonly used in the early stages of design when a large number of ideas are still under consideration. The throwaway prototype can also be used in late stage design in industries where the product is launched at a low level of refinement. The differences between evolutionary and throwaway prototypes are given in Table 1.1.

Table 1.1. Evolutionary prototype vs. throwaway prototype

	Evolutionary prototype	*Throwaway prototype*
Definition	A robust prototype that has been constantly developed.	An inexpensive, quick prototype that can be rapidly discarded.
Associated with	Refined products. Future concepts. State of the art demonstrations.	Early stage designs. Minimum viable products.

1.1.4. Differences Between Prototypes and Final Products

Generally creating prototypes will differ from creating the final product in numerous basic ways:

(*i*) *Material:* The materials that will be used in a final product can be costly or difficult to manufacture. Thus, prototypes can be made from different materials than the end product.

(*ii*) *Processes:* Mass production processes are frequently inappropriate for manufacturing a small number of parts. Thus, prototypes can be made using diverse manufacturing processes than the end product.

(*iii*) *Verification:* The end product can be subjected to a number of quality control tests to approve compliance with drawings or specifications. These tests may comprise custom inspection devices, statistical sampling methods and other methods suitable for the on-going production of a large quantity of the end product. Prototypes are usually made with much closer individual inspection and assuming that some adjustments or rework will be part of the manufacturing process. Prototypes can also be exempted from certain requirements that will apply to the end product.

Engineers and prototype specialists try to minimize the impact of these differences on the intended role of the prototype. For example, if a visual prototype is unable to use the same materials as the end product, they will attempt to replace materials whose properties closely mimic the planned final materials.

1.1.5. Limitations of Prototypes

Designers and prototyping experts try to understand the limitations of prototypes to exactly simulate the features of their proposed design.

It is essential to understand that by their nature, prototypes will represent a compromise to the final production design. Due to variances in materials, process and design fidelity, it is possible that a prototype will not perform acceptably while the production design may have been sound. A counter-intuitive idea is that the prototypes can actually perform in an acceptable way while production design can be flawed, as materials and prototyping processes can sometimes outperform their production counterparts.

In general, the costs of individual prototypes can be expected to be considerably higher than the final production costs due to inefficient materials and processes. Prototypes are also used to refine the design with the aim of reducing costs through optimization and refinement.

It is advantageous to use prototype testing to decrease the risk that a design will not perform as expected, but prototypes normally cannot exclude all risks. There are logical and practical limits to a prototype's capacity to match the intended final performance of the product, and certain tolerances and technical decisions are often required before moving on to a production design.

Building the complete design is often costly and can be time taking, particularly when repeated several times — build the entire design, figure out what the problems are and how to fix them, and then build another complete design. As an alternative, rapid prototyping or rapid application development techniques are used for the initial prototypes, which implement part, but not all, of the complete design. This allows designers and manufacturers to quickly and inexpensively test the parts of the design that are most likely to have problems, resolve those issues, and then build the complete design.

This counter-intuitive idea is the fastest way to build something else first which is shared by the scaffolding and the telescope ruler.

1.1.6. Examples of Prototypes

In technological research, a technology demonstrator is a prototype aiding as a proof of concept and demonstration model for a new technology or a future product, proving its feasibility and demonstrating possible applications.

In large development projects, a test bed is a prototype development platform and environment for rigorous experimentation and testing of new technologies, components, scientific theories and IT tools.

With recent advances in computer modelling, it becomes practical to eliminate the creation of a physical prototype (except perhaps at greatly reduced scales for promotional purposes), instead of modelling all aspects of the final product as a computer model. An example of such a development can be seen in the Boeing 787 Dreamliner, in which the first full-scale physical realization is carried out on the series production line. Computer modelling is now widely used in automotive design in both the form (in the styling and aerodynamics of the vehicle) and in function - especially to improve the impact resistance of vehicles and to reduce weight for improving mileage.

The most common use of the word prototype is a functional, though experimental, version of a non-military machine (e.g., automobiles, household appliances, consumer electronics) that the designers would like to have built by means of mass production, as opposed to a mock up simulation, which is a passive representation of the appearance of a machine, often made of an unsustainable substance.

An electronic designer often builds the first prototype from breadboard or strip board or perfboard, typically using "DIP" packages.

However, more and more often the first working prototype is built on a nearly identical 'prototype PCB' identical to the production PCB, as the manufacturing prices of PCBs drop and many components are not available in DIP packages, but only available in SMT packages optimized for placement on a PCB.

Manufacturers of military and aviation machinery prefer the terms "experimental" and "service test".

1.2. HISTORICAL DEVELOPMENT

1.2.1. Roots of AM

The roots of RP can be traced to two technical areas: *topography* and *photosculpture*.

Topography: A layered method was proposed by Blanther as early as 1890 to make molds for topographical relief maps. The positive and negative 3D surfaces were to be assembled from a series of wax plates cut along the topographical contour lines (Fig. 1.4). This technique has been advanced by Perera, Zang and Gaskin.

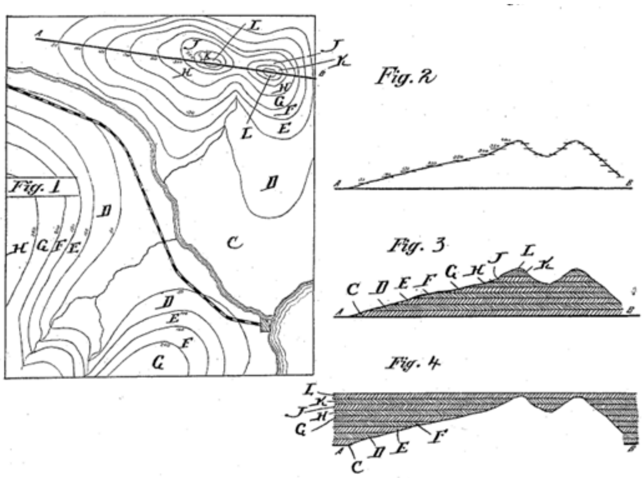

Fig. 1.4 A method for making moulds for topographical relief maps

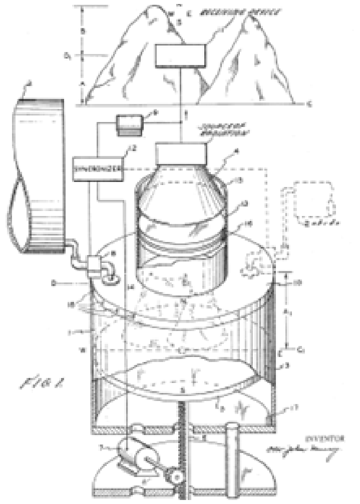

Fig. 1.5 The layer manufacturing system.

Matsubara explained a method of making layers to form casting molds. The layers of the molds are made from refractory particles coated with a photopolymer resin. The resin is selectively light cured. Likewise, DiMatteo proposed a method of manufacturing layers of 3D objects from profile contoured metal sheets which are formed using a milling cutter. Nakagawa reported the use of layering techniques for the manufacture of die cutting tools, press forming tools and injection molding tools.

Photosculpture: This technique was proposed in the 19th century to create replicas of 3D objects. The technique consists of photographing the object simultaneously with 24 cameras equally spaced around a circular piece and then using the silhouette of each photograph to sculpt 1/24th of a cylindrical part of the object. Attempts have been made by other developers to improve the technique by reducing the manual carving steps. Morioka proposed the use of structured lighting to create contour lines of an object photographically, then use those lines to cut and construct the object from sheets. In 1956, Munz patented a layering system (Fig. 1.5) to fabricate cross sections of a scanned object by selectively exposing a transparent photo emulsion. The system produces the layers by lowering a piston into a cylinder and adding suitable quantities of photo emulsion and fixing agent.

1.2.2. Patents filed on Different Methods and Systems

Development work in the field of AM continued in the 1960s and 1970s and a number of patents were filed on various processes and systems. These include:

- A method of making objects from powdered materials by heating the particles locally and fusing them together using a laser, electron beam or plasma beam.
- A process for producing plastic patterns by selective 3D polymerization of a photosensitive polymer at the intersection of two laser beams.
- An AM photopolymer system for the construction of layered objects. A mask is used to control the exposure of the UV source when producing a cross section of the model.
- A system that directs a UV laser beam to a polymer layer by means of a mirror system on an x-y plotter.

In addition to this list, there are number of patents covering current commercial AM processes. The most important patents enumerated by Beaman are shown in Table 1.2. The substantial increase in the number of commercially available AM systems in the 1990s can be explained by advances in 3D CAD modeling, computer aided manufacturing, and computer numerical control. These technologies were used initially in the fast growing and highly competitive high tech, automotive and aerospace industries. Another important aspect is that the application of AM has spread to other sectors of the economy (Fig. 1.6).

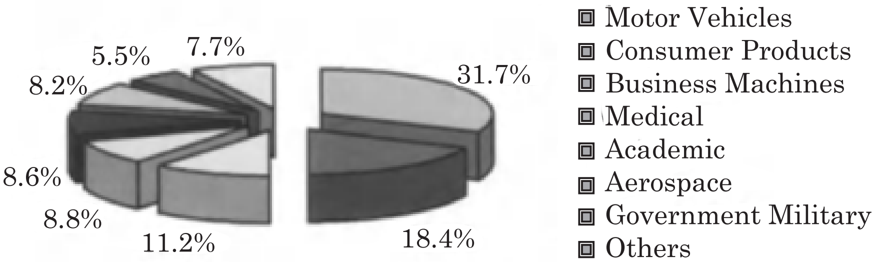

Fig. 1.6. The use of AM systems in different sectors.

This strong and steady growth in sales and the extensive use of the technology present very optimistic prospects for the AM industry and its future.

Table 1.2. Active AM patents

Name	Title	Filed	Country
Housholder	Moulding process	Dec-79	U.S.
Murutani	Optical mould method	May-84	Japan
Masters	Computer automated manufacturing process and system	Jul-84	U.S.
Andre et al.	Apparatus for making a model of an industrial part	Jul-84	France
Hull	Apparatus for making three-dimensional objects by stereolithography	Aug-84	U.S.
Pomerantz et al.	Three-dimensional mapping and modelling apparatus	Jun-86	Israel
Feygin	Apparatus and method for forming an integral object from laminations	Jun-86	U.S.
Deckard	Method and apparatus for producing parts by selective sintering	Oct-86	U.S.
Fudim	Method and apparatus for producing three-dimensional objects by photosolidification; radiating an uncured photopolymer	Feb-87	U.S.
Arcella et al.	Casting shapes	Mar-87	U.S.
Crump	Apparatus and method for creating three-dimensional objects	Oct-89	U.S.
Hclinski	Method and means for constructing three-dimensional articles by particle deposition	Nov-89	U.S.
Marcus	Gas phase selective beam deposition: three-dimensional, computer-controlled	Dec-89	U.S.
Sachs, et al.	Three-dimensional printing	Dec-89	U.S.
Levent, et al.	Method and apparatus for fabricating three-dimensional articles by thermal spray deposition	Dec-90	U.S.
Penn	System, method, and process for making three-dimensional objects	Jun-92	U.S.

1.3. FUNDAMENTALS OF ADDITIVE MANUFACTURING

The additive manufacturing process adds material in consecutive layers to make the desired shape instead of removing material to create a part (Fig. 1.7).

Fig.1.7. 3D printing

Additive manufacturing technology is called the generative manufacturing process (GMP) because the shape of the work piece is not achieved by chip removal or by forming or moulding. It is obtained by adding material without any shape or form recognizable beforehand and no tools are necessary. In all types of GMP, the CAD model is divided into layers as shown in Fig. 1.8. As any imaginable part can be cut (at least virtually), any part can be divided into slices, regardless of its geometry.

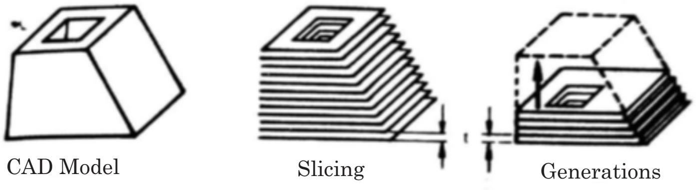

Fig. 1.8. Basic principle of the GMP

Slice thickness and slicing direction can be changed to facilitate generation. To generate an object with the same shape as that of the sliced CAD model, the distance between the slicing planes (*t*) must be equal to the thickness of the corresponding layers during the actual generation process.

Most machines build layers of the order of 0.1mm, but there are machines that process layers with a thickness of 0.016 mm and machines that deliver layers around 0.2 mm thick.

The component to be created will be represented by a set of 3D CAD data. The data is practically sliced into layers of uniform layer thickness using a so-called slice algorithm. This provides the contour data and the layer thickness of each layer (Fig. 1.9). The AM machine transfers the virtual data into actual layers and joins each layer to the previous one. The thickness of the layer being constant, the part has a *stair–stepping effect* on its surface.

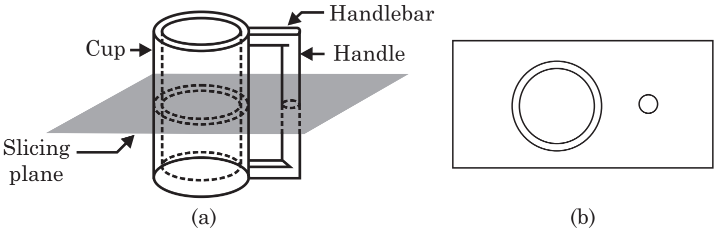

Fig.1.9. Conversion of a solid model of an object into layers (only one layer is shown)

AM uses software that slices the 3D model into layers (0.01mm thick or less in maximum cases). Each layer is then plotted on the build plate by the printer, when the pattern is completed the build plate is lowered and the next layer is added on top of the previous one. A 3D print model is a file that a 3D printer can read and interpret. It is used to tell the 3D printer where to place the nozzle in order to create the physical object. The template file contains geometric information that must be interpreted by slicing software that transforms the geometric input into commands and allows the printer to process.

Typical manufacturing techniques are known as "subtractive manufacturing" because the process involves removing material from a preformed block. Processes such as drilling and slicing are subtractive manufacturing techniques (Fig. 1.10). This type of process creates a lot of waste since; the cut material usually cannot be used for anything else and is just discarded as scrap.

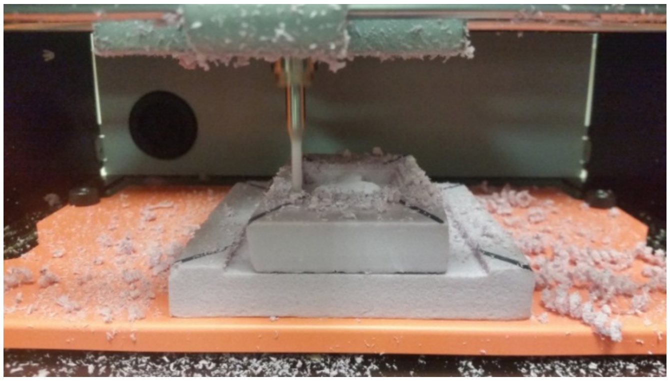

Fig. 1.10. Subtractive manufacturing process (drilling)

1.3.1. Layer Based Technology

The principle of layer-based technology is to create a three-dimensional physical object called a "part" from several layers of (generally) equal thickness. Each layer is profiled according to the corresponding three-dimensional data set (Fig. 1.11) and placed on top of the previous one. As a consequence of the uniform thickness of the layer, the resulting part exhibits a stair-stepping effect as shown in Fig. 1.11(b).

(a) (b)

Fig. 1.11. Principle of layer manufacturing
(a) Contoured layers, (b) 3D object made from staggered layers

Almost all RP systems use layering technology in the creation of prototype parts. The basic principle is the availability of computer software to cut a layered CAD model and reproduce it in an "output" device such as a laser scanning system. The layer thickness is controlled by a precision elevator mechanism. It will directly correspond to the layer thickness of the computer model and the cured thickness of the resin. The limiting aspect of the AM system tends to be the curing thickness rather than the resolution of the elevator mechanism. The important part of the building process is the laser and its optical scanning system.

Additive manufacturing is an automated, layer-based manufacturing process to create scaled three-dimensional physical objects directly from 3D CAD data without the use of part-dependent tools. It was formerly called "3D printing" and is still often called that.

Along with well-established "subtractive manufacturing" such as milling or turning, and "formative manufacturing" such as casting or forging, additive manufacturing forms the third pillar of manufacturing technology.

When the first approaches to "additive manufacturing" entered the market in 1987, they were called "rapid prototyping" or "generative manufacturing". Both terms are still in use and in recent years many different names have been introduced. While each of the names is correct

A Treatise on

ADDITIVE MANUFACTURING

About the Book

A treatise on Additive Manufacturing (AM) is a concise textbook that takes readers inside the world of additive manufacturing. This book provides a very basic and essential knowledge about different types of AM technologies, available models and their specifications, advantages, disadvantages, potential applications and a few case studies. Easy to understand, this book gives good introduction to anyone interested in obtaining a better understanding of AM.

Salient Features

Focusing on additive manufacturing applications rather than on core AM technologies, this book :

- Introduces various additive manufacturing technologies based on their utilization in different classes of materials.
- Reflects recent developments and trends and adheres to the ASTM, SI and other standards.
- Includes a section on automotive, aerospace and medical applications.
- Includes discussions of the specifications and special aspects of industrially available machines.
- Provides the latest information on the use of additive manufacturing for the direct production of finished products.
- Provides a broad range of technical (subjective and objective) questions to ensure comprehensive understanding of the concepts covered.

About the Author

Dr. R. B. Choudary, Academic Director, Minerva Group of Institutions, Prathipadu has more than three decades of teaching experience in various Engineering Colleges. He received *Best Paper Award*, ISRS-2007, Chennai and *Modi Award*, NWS-1991, Madras. He authored five text books *viz.* Plant Layout and Materials Handling, Engineering Graphics with a primer on AutoCAD-2016, Materials Science and Metallurgy, Ansys R2020, Non-destructive Testing and several research papers.

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