# The 3D Printing Handbook

## Technologies, design and applications

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PROTOLABS
Manufacturing. Accelerated.

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**Book printed by**
Coers & Roest

**ISBN**
978-90-827485-0-5
Protolabs Europe B.V.





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## Credits

This book would not be nearly as complete without the dedication and contributions of an incredible amount of industry experts, manufacturers, and above all, the supportive 3D printing community from all around the world.

First and foremost, a huge thank you to the people who gave their time to review and provide feedback on the text in this book; **Michael Molitch-Hou** (Engineering.com), **Sarah Goehrke** (3Dprint.com), **Bill Artley** (Print Form), **Alan Nguyen** (Space Junk Co), **Dr. Joshua M. Pearce** (Michigan Tech), **Richard Smith** (Oxford University), **Andreas Bastian** (Autodesk), **Erik de Bruijn** (Ultimaker), **Florian van der Horst** (Oceanz), **Chris Mcaloney** (Proto3000), **Tobias Tuffentsammer** (ExOne), and **Dr. Hisham Alkabie** (EQT Aerospace & Defence).

For their expert contributions as authors: thanks to **Courtney Armstrong** on designing for SLA/DLP, **Perry Cain** on layer height and support for FFF, **James Low** on snap fit connections, **Ben Hudson** on designing for FFF, **Alkaios Bournias Varotsis** for his clarifications on the differences between desktop and industrial FFF printing, **Diederik van der Steen** on post processing and desktop vs. industrial SLA/DLP, **Stefan Holdinga** on designing for SLS, **Chris McAloney** on designing for material jetting, **Martin Petrak** on designing for DMLS/SLM, **John Wall** on enclosure design, **Bill Artley** on applications in automotive, **Thomas van de Hout** on topology optimization, **Joris Peelz** for his ever available expertise, **Jack Davies** for his contribution on reverse engineering and CAD software, **Robin Brockötter** on surface modeling and **George Fisher-Wilson** for his 3D printing case studies.

Many thanks also go to the following companies who provided us with the world-class case studies for Part 3 of this book; **Ultimaker & Volkswagen AutoEuropa** and **PEAK Industrie**s for applications in FFF. **Formlabs** and **EnvisionTec** for SLA/DLP, **Paul Kohlhaussen Design** and Rehook for SLS, **Mark Thielen** & **Eindhoven University** and **Vitaly Bulgarov** & **Factor 31** for material jetting, **ExOne** for binder jetting, **Concept Laser** and **Thomas van de Hout** for their DMLS/SLM case studies.

Special thanks must go to the entire team for tirelessly proofreading version after version and continuously pointing out improvements along the way. **Tom Debicki** for creating the design concept of the book, creating hundreds of versions of illustrations and all the infographics, **Ken Giang** for the world-class photography, and **Bram de Zwart** who supported the project every step of the way.

And finally, a big thanks goes to the design team from **Multitude** for helping bring this book from a concept into reality and getting this book to production with no compromise on quality.

# Foreword

It is the summer of 2001 in Cupertino, California, I stare at a lump of foam, some lego-like mechanical elements and an assortment of electrical components scattered across a desk. My task was a tough one; to create the first prototype of a new product I had been contracted to design for Apple.

The project brief was to create a device that could be a modern day Sony Walkman for the MP3 generation. It took hard work, dozens of design iterations and lots of foam but it was complete. The creation that would go on to become the first iPod prototype, and a decade of various future iPod incarnations which ultimately grew up to become the iPhone.

When creating new products you're always looking to make something that's much better, visibly and functionally, than what's available. Whether it's hardware or software that you're designing, at the core of it is the drive to create something new, disruptive, and emotional. With real innovation comes the need to prototype; if it's not been done before, your first attempt is probably not going to be the one you run to the market with. Iteration is key.



The way in which prototypes are designed, produced and modified has come a long way since creating that first iPod at Apple. Readily available and affordable prototyping via 3D printing is now a reality. The speed in which you can generate ideas into physical objects is now faster than it has ever been. We live in a world full of tools and resources that allow us to create and innovate with ease. The next step is to apply these resources as forces of disruption and change.

This really hits home the importance of 3D printing and how it can work for anyone involved in designing or manufacturing physical objects. Innovative and complex product design needs prototyping. It takes time but in the end these are the tools that allow you to make those big decisions. Everything we were doing at Apple, back then, was brand new to the world of technology, which meant we had to continually evolve to find the right path. Part of this evolution set the foundation for others to adopt and improve the technology we developed later on.

"The Handbook" will help to guide you on your own path as you look to leverage 3D printing and its potential to create your own breakthrough products, that hopefully will change the world. Every designer and engineer should keep it close as it paves your way into new manufacturing technologies that will spur your creativity and unlock your ideas as they become reality. Creation is changing, manufacturing is changing and design is changing, turn the page it's time to stay ahead...

Tony Fadell

Creator of the iPod and founder of Nest

# How to use this book

The 3D Printing Handbook is written for designers and engineers to quickly master the key aspects of 3D printing. It is specifically intended to provide practical advice on how to select a 3D printing technology, including decision making tools and design guidelines. The book is in principle not targeted at machine operators, for which more in-depth, machine specific documentation is available. Having a basic understanding of manufacturing technologies will help but is not essential.

To make the book actionable for the reader, the content is based upon first-hand experience from machine operators and industry experts. Unlike other books, this book is not meant to be read from front to back. Instead, several features have been included to help the reader find the information they are looking for.



## Three Parts

This book is split into 3 distinctive Parts;

- **Part 1** – gives a comprehensive overview the most common 3D printing technologies including specifications, materials and post processing. This is the best place to start for readers unfamiliar with 3D printing. ▷ SEE PAGE 16
- **Part 2** – focuses on actionable design advice for each technology. This section is for readers who are familiar with 3D printing and want a set of clear design rules to follow, to ensure parts and features are printed to specification. ▷ SEE PAGE 144
- **Part 3** – includes an introduction to Computer Aided Design (CAD) software and presents a range of case studies highlighting the strengths of each of the 3D printing technologies discussed in Part 1 and 2. ▷ SEE PAGE 226

Each Part is clearly separated by a full red page indicating where the new Part begins.

## Keywords

Highlighted keywords are shown in the margins of each page. → KEYWORDS

These keywords allow the reader to quickly flick through the book and identify relevant sections or words of interest. The keywords are reflections of words or terms that the authors have deemed important. For instant navigation, all keywords are found in the Index. ▷ SEE PAGE 286

## Decision making tools

One of the main goals of this book is to allow the reader to select an appropriate technology for a given application. To aid in this, the concluding chapters of Part 1 and 2 include decision making tools, allowing the reader to quickly compare the different methods of 3D printing. ▷ SEE PAGE 16, 144

Chapter 8 comprises of two such tools; a summary table of all 3D printing technologies, and a decision making tree for determining the best technology based on a few basic requirements. Chapter 17 consists of a useful summary table of all the design rules discussed in Part 2 on a per technology basis. ▷ SEE PAGE 137 ▷ SEE PAGE 223 ▷ SEE PAGE 144

# Introduction

As an engineer, often the most important consideration when designing parts for production is the method of manufacturing. A design can be produced via a range of manufacturing techniques with each having their own associated strengths and weaknesses.

The purpose of this introduction is to identify where 3D printing sits as a method of manufacturing relative to more traditional processes, like CNC, injection molding and casting. This section will outline the most common manufacturing methods and conclude with an overview of the general 3D printing process. A detailed explanation of manufacturing technologies other than of 3D printing is outside the scope of this book.



## Classification of manufacturing techniques

Most manufacturing techniques can be categorized into 3 groups. At the simplest level these groups can be defined as:

- **Formative manufacturing:** best suited for high volume production of the same part, requiring a large initial investment in tooling (molds) but then being able to produce parts quickly and at a very low unit price.

TOOLING

- **Subtractive manufacturing:** lies in between formative and additive, being best suited for parts with relatively simple geometries, produced at low-mid volumes, that are typically made from functional materials (particularly metal).
- **Additive manufacturing:** best suited for low volume, complex designs that formative or subtractive methods are unable to produce, or when a unique one-off rapid prototype is required.

RAPID PROTOTYPE

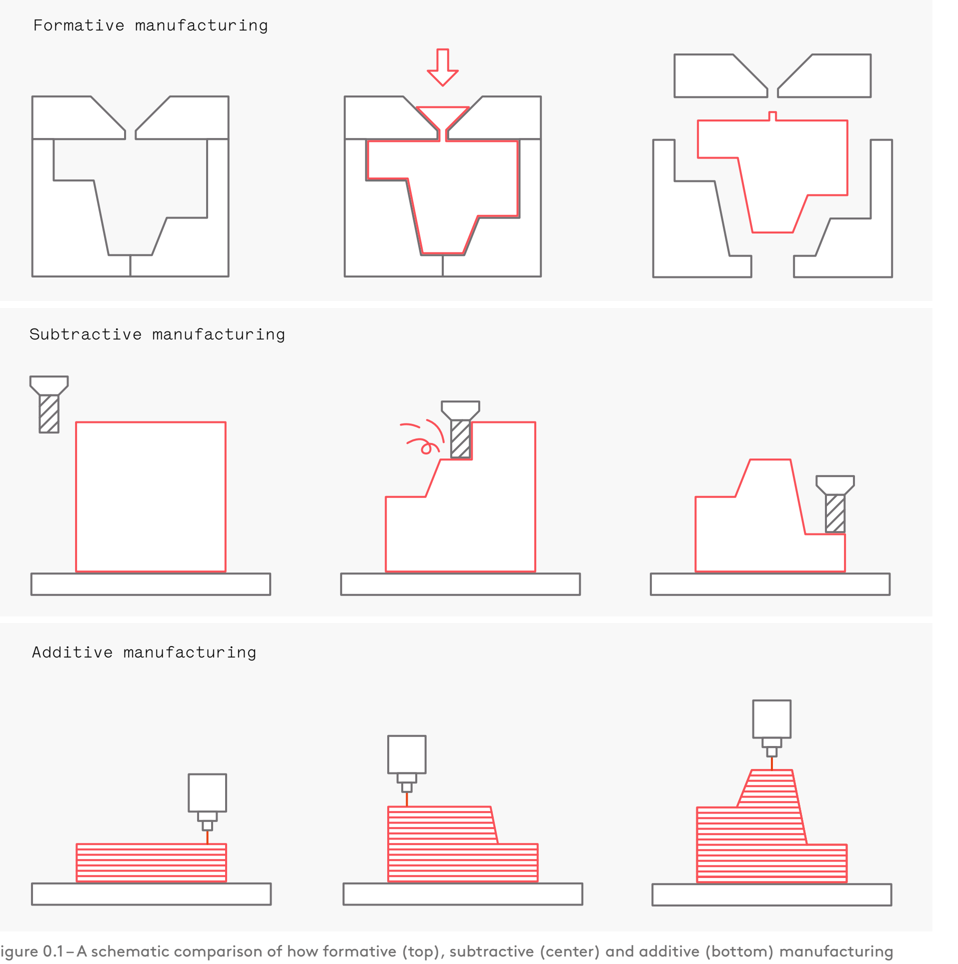



Figure 0.1 – A schematic comparison of how formative (top), subtractive (center) and additive (bottom) manufacturing techniques produce parts

## Formative (injection molding, casting, stamping and forging)

Formative manufacturing typically forms material into the desired shape via heat and pressure. The raw material can be melted down and extruded under pressure into a mold (injection molding/die casting), melted and then poured into a mold (casting) or pressed or pulled into the desired shape (stamping/vacuum forming/forging). Formative techniques produce parts from a large range of materials (both metals and plastics). For high volume production of parts, formative manufacturing is often unrivaled in cost. The main limitation of formative manufacturing is the need to produce a tool (mold or die) to form the part. Tooling is often expensive and complicated to produce, increasing lead times and delaying the manufacturing of a part. This large upfront investment is why formative manufacturing is generally only cost effective at high volumes.

HIGH VOLUME PRODUCTION

The design of formative tooling is also complex with the need for mold features like spurs or runners to assist in the formation of parts. Parts that are produced via formative manufacturing also have design constraints like draft angles and uniform wall thickness to aid in the forming process.

MOLD FEATURES

## Subtractive (CNC, turning, drilling)

Subtractive manufacturing begins with a block of solid material (blank), and utilizes cutting tools to remove (machine) material to achieve a final shape. CNC milling, turning (lathe) and machine operations like drilling and cutting are all examples of subtractive techniques.

Subtractive manufacturing is capable of producing highly accurate parts with excellent surface finish. Almost every material is able to be machined in some way. For majority of designs, subtractive manufacturing is the most cost effective method of production.

Subtractive manufacturing is limited by a number of factors. Most designs require Computer Aided Manufacturing (CAM) to plot tool paths and efficient material removal. This adds time and cost to the overall process. Tool access must also be considered when designing parts for subtractive manufacturing as the cutting tool must be able to reach all surfaces to remove material.

TOOL ACCESS

While machines like 5-axis CNC eliminate some of these restrictions, complex parts will need to be re-orientated during the machining process, further increasing cost and lead time. Subtractive manufacturing is also generally considered a wasteful process, due to the large amounts of material that is often removed to produce the final part geometry.



## Additive (3D printing)

Additive manufacturing (more commonly known as 3D printing) is the process of additively building up a part one layer at a time. There are a range of 3D printing technologies with each having their own benefits and limitations and each being able to print parts from different materials.

Parts can be produced in almost any geometry, which is one of the core strengths of 3D printing (even though there are still rules that must be followed per technology). Also, 3D printing does not rely on expensive tooling having essentially no start up costs. The advantage of this is the rapid verification and development of prototypes and low-volume production parts.

NO START UP COSTS

One of the biggest limitations of 3D printing is the inability to produce parts with material properties equivalent to those made via subtractive or formative techniques. Most 3D printing technologies produce parts that are inherently anisotropic or not fully dense. 3D printing also has limitations on repeatability, meaning parts will often have slight variations due to differential cooling or warping during curing.

ANISOTROPIC

## Cost comparison

Cost is often the governing factor behind how a part will be manufactured. Figure 0.2 gives a general insight into how the cost of manufacturing (cost per part) varies based on the amount of parts being produced.

COST PER PART

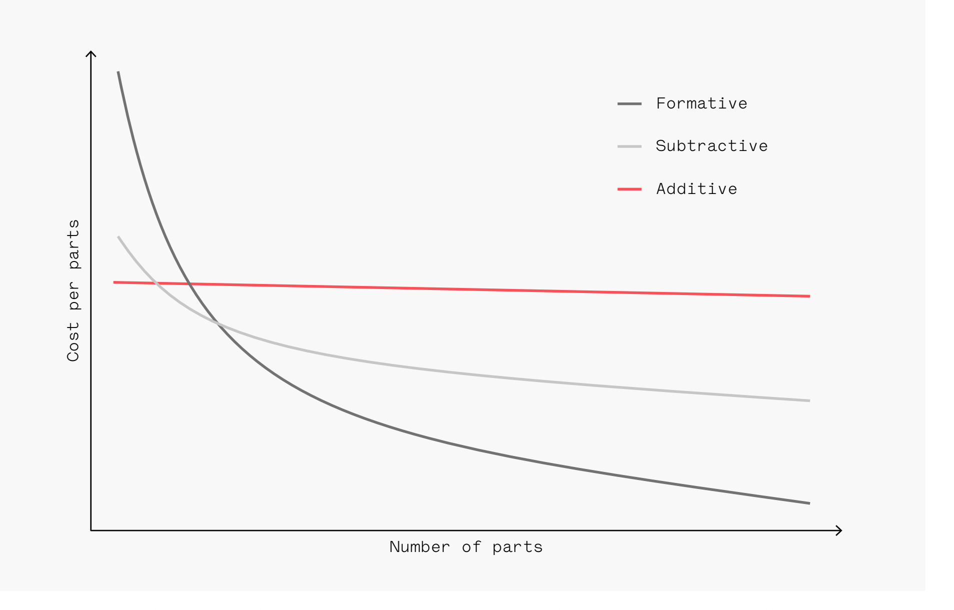



Figure 0.2 – In terms of economies of scale, higher volumes formative manufacturing is the most cost effective solution. The limiting factor behind this is whether a design is able to be produced formatively

## The 3D printing process

While there are many different 3D printing technologies, the following section will focus on the general process from design to final part. Although each method of 3D printing produces parts in a different way, these 5 core steps are constant across all technologies.

### 1. Producing a 3D file

CAD

▷ SEE PAGE 229

Producing a digital model is the first step in the 3D printing process. The most common method for producing a digital model (Figure 0.3) is Computer Aided Design (CAD). Reverse engineering can also be used to generate a digital model via 3D scanning. Both CAD modeling and reverse engineering are discussed in Chapter 18 of this book.

▷ SEE PAGE 144

There are several design considerations that must be evaluated when designing for 3D printing. These generally focus on feature geometry limitations, support material and escape hole requirements. Designing parts for 3D printing is discussed in Part 2 of this book.

### 2. STL creation and file manipulation

STL FILE

OBJ, 3DP

SLICER PROGRAM

In order to 3D print a part, a CAD model must be converted into a format that a 3D printer is able to interpret. This begins by converting the CAD model into a STereoLithography (STL) file, also referred to as Standard Triangle Language file. OBJ or 3DP are also acceptable types of 3D printing file types but are less common. STL uses triangles (polygons) to describe the surfaces of an object, essentially simplifying the often complex CAD model. Most CAD programs are capable of exporting a model as an STL file.

Once a STL file has been generated, the file is imported into a slicer program, which slices the design into the layers that will be used to build up the part. The slicer program takes the STL file and converts it into G-code. G-code is a numerical control programming language used in CAM to control automated machines like CNC machines and 3D printers.

The slicer program also allows the 3D printer operator to define the 3D printer build parameters by specifying support location, layer height, and part orientation (Figure 0.4). Slicer programs are often proprietary to each brand of 3D printer, although there are some universal slicer programs like Netfabb, Simplify3D and Slic3r.

As a designer, it is generally only necessary to provide a 3D printer operator with an STL file. The operator will then set the desired parameters for the print and produce the G-code file themselves.

### 3. Printing

▷ SEE PAGE 16

Each of the 3D printing technologies discussed in this book additively manufacture parts differently. A detailed explanation on how each 3D printing technology produces parts, as well as the materials associated with each, are presented in Part 1 of this book.

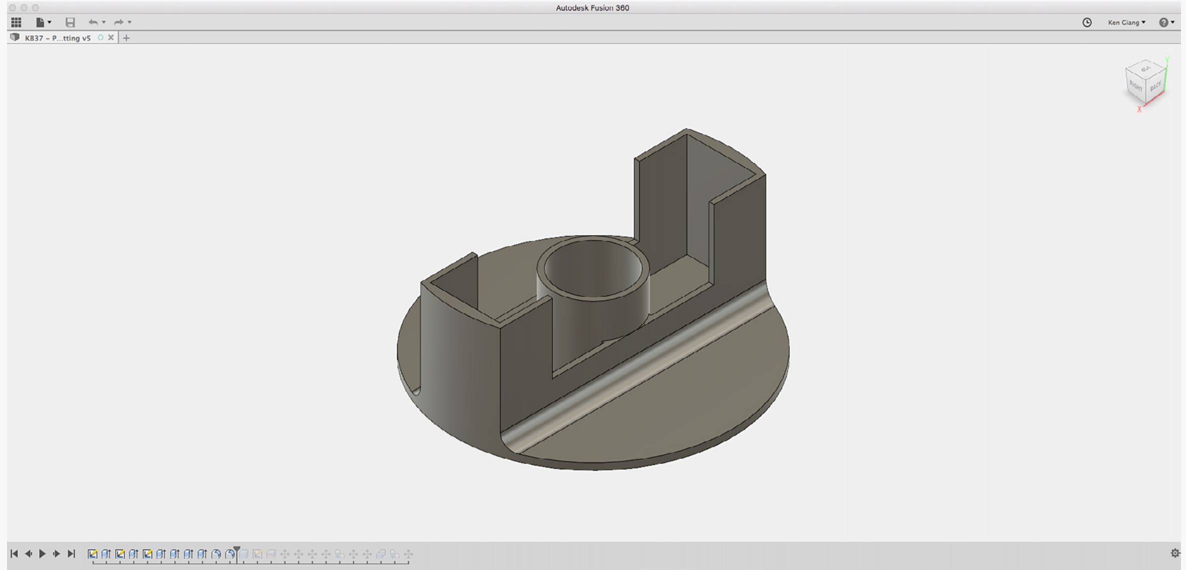


Figure 0.3 – A 3D CAD model of a shaft end cap produced in Autodesk Fusion 360. An STL file can be exported from the CAD program. The diameter of the cap is 40 mm

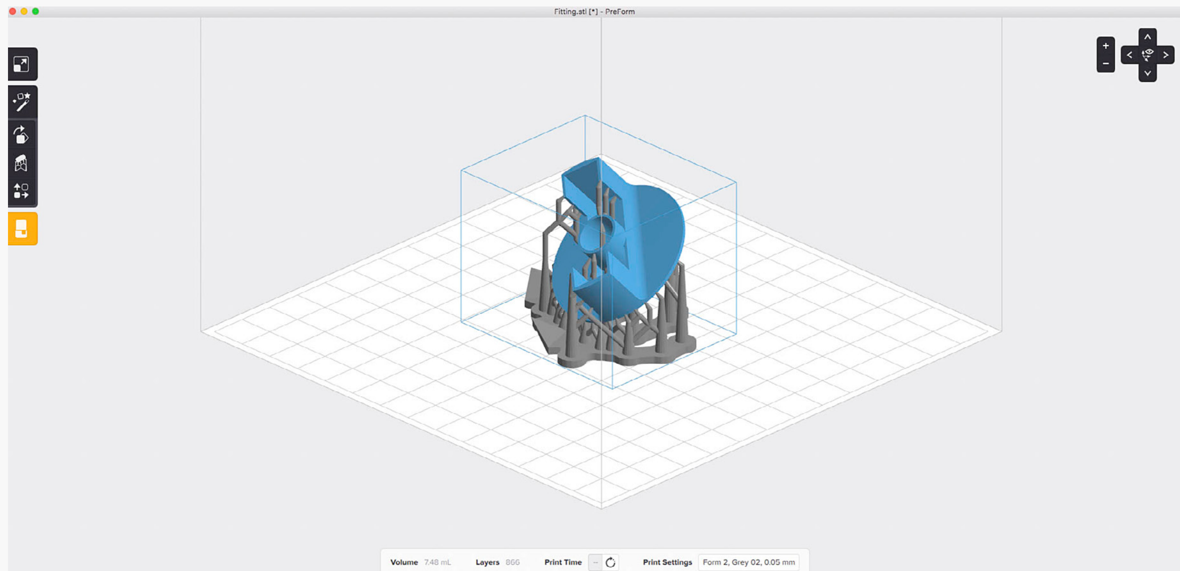


Figure 0.4 – Importing the STL file into the Formlabs slicing program Preform. The slicing programs allow for the shaft end caps' orientation to be defined as well as where support material is located

Figure 0.5 – The finished shaft end cap on the Formlabs Form 2 before being removed from the build platform. Print time for the motor housing cap was approximately 1.5 hours

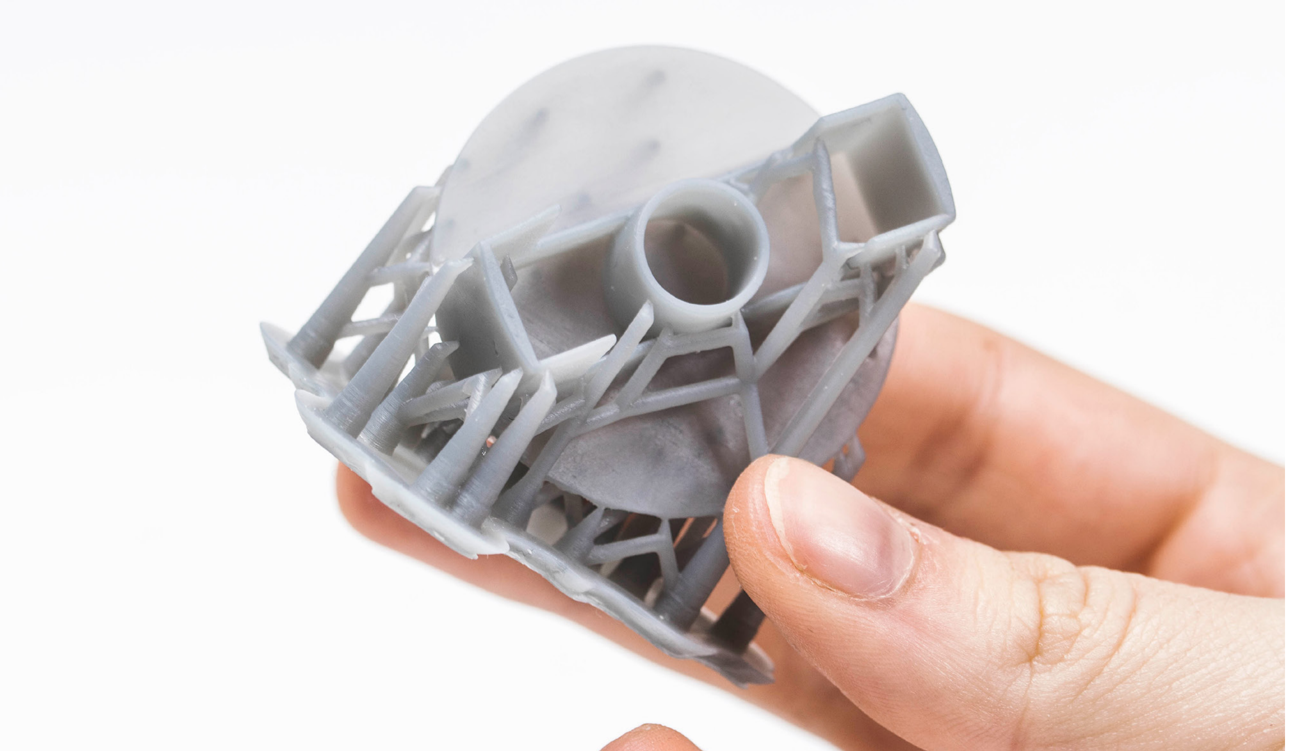


Figure 0.6 – The shaft end cap after being removed from the build platform with support structures still attached

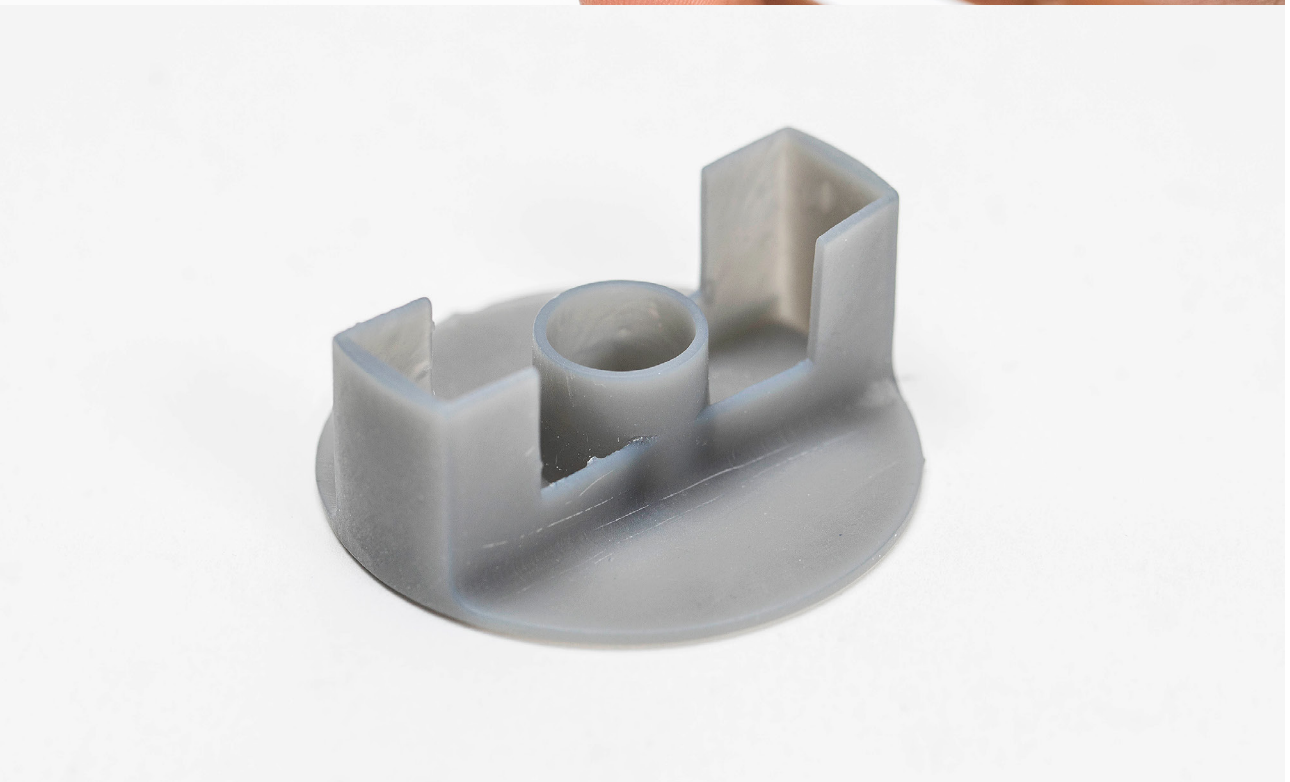


Figure 0.7 – The finished shaft end cap with support structures removed



**4. Removal of prints**
For some 3D printing technologies, removal of the print is as simple as separating the printed part from the build platform (Figure 0.6). For other more industrial 3D printing methods, the removal of a print is a highly technical process involving precise extraction of the print while it is still encased in the build material or attached to the build plate. These methods generally also require strict removal procedures and highly skilled machine operators along with safety equipment and controlled environments.

**5. Post processing**
Post processing procedures again vary by printer technology. Some technologies requires a component to cure under UV before handling while others allow parts to be handled right away. For technologies that utilize support, this is also removed at the post processing stage (Figure 0.7). The most common post processing options for each method of 3D printing are discussed throughout Part 1.

▷ SEE PAGE 16

The best way to determine whether a certain method of 3D printing is suitable for an application is to understand the mechanisms behind how the technology produces parts. Part 1 of this book aims to answer this question by introducing the most common methods of 3D printing and how each of them additively manufacture parts.

# Part One



# 3D Printing Technologies and Materials

## Introduction

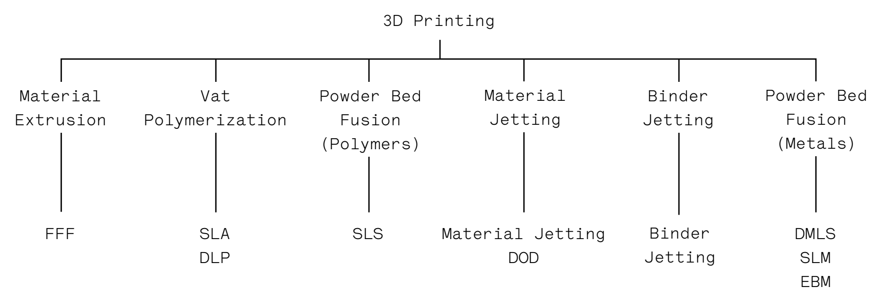
One of the most challenging tasks facing designers and engineers new to 3D printing is having to navigate through the vast number of technologies and materials that are available in order to determine the solution that is best suited for their application.

The following chapters will offer a detailed explanation into how each technology works, the common materials associated with each technology and their most common applications. Using this information it should be possible to determine which technology is best suited for a specific design. Part 2 of this book introduces specific design rules for each technology.



# 01

## Overview of 3D Printing




Selecting the optimal 3D printing process for a particular design can be difficult. The range of 3D printing methods and materials means that often several processes are suitable with each offering variations in properties like dimensional accuracy, surface finish and post processing requirements.

This Chapter introduces how 3D printing technologies and materials are categorized.

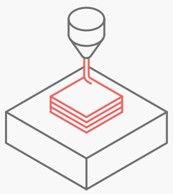
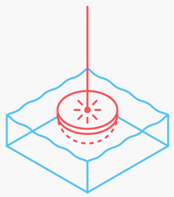
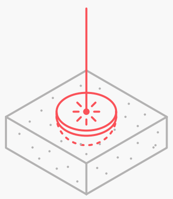
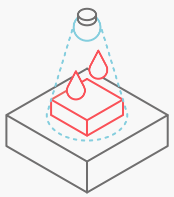
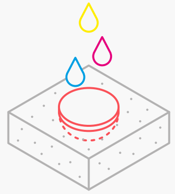
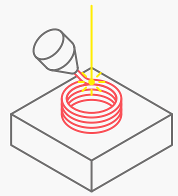
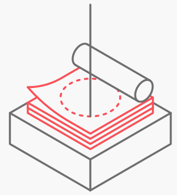
ISO/ASTM 52900

## 1.1 Classification of 3D printing technologies

The ISO/ASTM 52900 Standard was created in 2015 to standardize all terminology as well as classify each of the different methods of 3D printing. A total of seven process categories were established. Each of these and the associated process description are presented in Table 1.1.

*Note: With respect to the technologies discussed in this book, the less widely available 3D printing methods, like Direct Energy Deposition or Sheet Lamination, are outside the scope of this edition. We aim to add these technologies in future releases of this book.*

Table 1.1 – Classification of 3D printing technologies

| Process | Description | Technologies |
|---|---|---|
| Material Extrusion  | Additive manufacturing process in which material is selectively dispensed through a nozzle or orifice. | Fused Filament Fabrication (FFF), more commonly referred to as Fused Deposition Modeling (FDM) |
| Vat Polymerization  | Additive manufacturing process in which a liquid photopolymer in a vat is selectively cured by light-activated polymerization. | Stereolithography (SLA), Direct Light Processing (DLP) |
| Powder Bed Fusion  | Additive manufacturing process in which thermal energy selectively fuses regions of a powder bed. | Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM) |
| Material Jetting  | Additive manufacturing process in which droplets of material are selectively deposited and cured on a build plate. | Material Jetting (MJ), Drop On Demand (DOD) |
| Binder Jetting  | Additive manufacturing process in which a liquid bonding agent selectively binds regions of a powder bed. | Binder Jetting (BJ) |
| Direct Energy Deposition  | Additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. | Laser Engineering Net Shaping (LENS), Laser-Based Metal Deposition (LBMD) |
| Sheet Lamination  | Additive manufacturing process in which sheets of material are bonded to form a part. | Ultrasonic Additive Manufacturing (UAM), Laminated Object Manufacturing (LOM) |



## 1.2 3D Printing Material Groups

Like 3D printing technologies, 3D printing materials can also be separated into categories. The majority of 3D printing materials can be separated into 2 groups; polymers and metals (Figure 1.1).

▷ SEE PAGE 22

### 1.2.1 Polymers

Polymers, such as plastics, come in many different forms and their diversity of properties sees them used for a wide range of applications. Polymers are found in everything from adhesives to biomedical devices. Today, the polymer industry is larger than the steel, aluminum and copper industries combined.

Polymers in 3D printing generally come in three different forms: filament, resin and powder (Figure 1.2). Polymers in 3D printing are generally divided into two categories: thermoplastics and thermosets. They differ mainly in their thermal behavior.

▷ SEE PAGE 23

#### Thermoplastics

THERMOPLASTICS

Thermoplastics can be melted and solidified over and over again while generally retaining their properties. Both traditional injection molding, as well as the FFF printing processes, make use of thermoplastics by heating up solid thermoplastic to a malleable state and injecting or extruding it into a die or onto a build platform where it then solidifies. Common thermoplastic products include plastic bottles, LEGO bricks and food packaging.

THERMOSETS

**Thermosets**

Unlike thermoplastics, thermosets do not melt. Thermosets typically start as a viscous fluid and are cured to become solid. Curing can occur via heat, light exposure or by mixing with a catalyst. Once solid, thermosets cannot be melted and instead will lose structural integrity when subjected to high temperatures. The SLA/DLP and Material Jetting processes use photopolymer thermosets that harden when exposed to a laser or UV light. Common thermoset products include two-part epoxies, bowling balls and high temperature components, like the knobs on a stove top.

### 1.2.2 Metal

Unlike polymers, which are used in a variety of forms (solid filaments, powder, resins), metal 3D printing almost exclusively uses powders. Metal printing allows for high-quality, functional and load bearing parts to be produced from a variety of metallic powders. Particle size distribution, shape and flowability (the collective forces acting on individual particles as they flow) are all important properties that govern how appropriate a metal powder is for 3D printing.

### 1.2.3 Other

COMPOSITES

Some 3D printing technologies make use of ceramics (typically a polymer filled with ceramic powder) or composites (chopped carbon-filled filaments or metal-nylon powder).

Polymers filled with ceramic powder have improved wear resistance, making them ideal materials for tooling applications. SLA printing, for example, offers a ceramic powder filled resin used for the production of high detail injection molds. Carbon, aluminum, graphite and glass are all added to SLS powder increasing strength-to-weight performance, wear resistance and static resistance. FFF has many exotic filaments available, like wood- or metal-filled PLA, resulting in a unique part appearance.

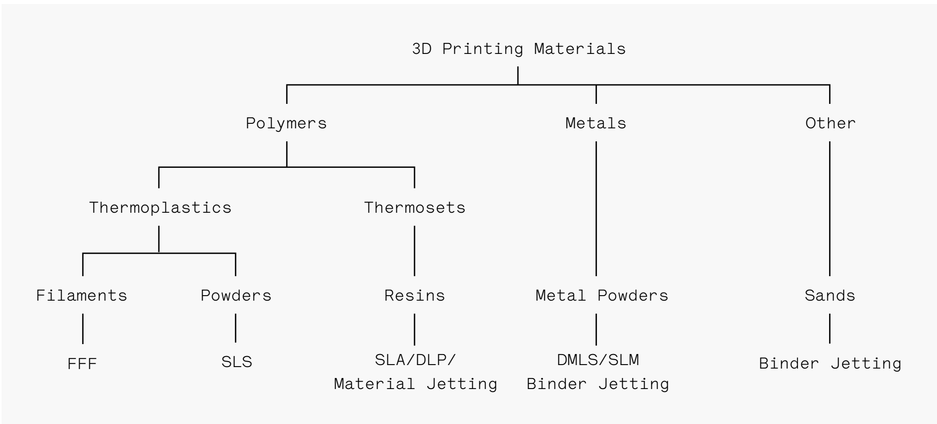



Figure 1.1 – 3D printing material classification




Figure 1.2 – An FFF filament spool (left), SLS nylon powder (center) and a tank of SLA resin (right)


Figure 1.3 – A range of different 3D printed materials showing 1. ABS (FFF), 2. rigid opaque resin (Material Jetting), 3. graphite-reinforced nylon (SLS), 4. transparent resin (SLA), 5. carbon-reinforced nylon (CFF), 6. ultra clear resin (Material Jetting), 7. HP nylon (Multi Jet Fusion), 8. castable resin (DLP), 9. grey PA12 nylon (SLS), 10. white PA12 nylon (SLS), 11. tool steel (DMLS)