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Fundamentals and Applications of Additive Manufacturing

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Abstract
Additive Manufacturing (AM) is a fabrication technique that builds up materials to create a three-dimensional form. Rapid prototyping and customized design solutions have made use of AM in conjunction with computer-aided design. The development of AM is a viable option to produce any type of prototype model by recent improvements in AM materials, methods, and printers' work volumes. The actual design of model, which is carried out digitally, is only one aspect of the design that may be customized. Materials and composites that may be too complex for conventional manufacturing processes, can be explored in additive manufacturing. Additionally, as AM gains popularity, it may be possible to find more practical applications. This chapter discusses the fundamentals, types and applications of additive manufacturing.

***Keywords*:** Additive manufacturing, layer manufacturing, layer-based technology, rapid prototyping, rapid manufacturing, rapid tooling, indirect prototyping, indirect tooling

1.1 Basics and Definitions

1.1.1 Additive Manufacturing

Additive manufacturing produces scaled, 3D substantial objects from CAD data without the requirement for part-dependent machinery. The term "3D Printing" was first used and is being used commonly today. The third supporting pillar of the overall manufacturing method is provided by additive manufacturing, which works in conjunction with the well-known "Subtractive Manufacturing" techniques like turning and the "Formative Manufacturing" techniques like casting. The initial methods of AM were known as "Rapid Prototyping" when they first appeared on the market in 1987. Both terms are still in common usage, and throughout the years, countless other names have been suggested as well as

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frequent additions of new ones. Although every name is ideal from the unique perspective of its originator, many of them lead to confusion [1]. This is typically one of the factors that newcomers to the field of AM confront when they feel lost.

A limited number of the most often used terms are organized into a few families of key phrases to create a concise overview. Term usage examples include:

Digital – Digital Fabrication
Layer – Layer Based Manufacturing
Layer Oriented Manufacturing
3D – 3D Printing
Direct – Direct Manufacturing, Direct Tooling
Additive – Digital Manufacturing
Additive Manufacturing

Rapid – Rapid Prototyping, Rapid Tooling, Rapid Manufacturing, Rapid Technology

Aside from some early work in Germany in the 1990s, there were hardly any initiatives for standardization because Additive Manufacturing (AM) is a relatively new technology. The German Society of Mechanical Engineers oversaw the creation of a specific guideline on rapid prototyping in 2007. It was released in the autumn of 2008. The creation of their own standardization methods was begun in 2009 by ASTM and ASME. Standard Terminology for Additive Manufacturing techniques was another name for the committee F42 on Additive Manufacturing in the autumn of 2009. This group defined the term "Additive Manufacturing," among other things.

1.1.2 Theory of Layer-Based Technology

Like "Generative Manufacturing," the phrase "additive manufacturing" refers to any technique for combining material to produce a 3D physical part. Layer-based technology is the term used to describe how AM is technically implemented. As a result, the words layer-based technology, generative manufacturing, and additive manufacturing are now used interchangeably. As additional additive technologies become available in the future, they will need to be categorized according to the standards now used for AM. As an illustration, a method known as Ballistic Particle Manufacturing (BPM) which was first developed in 1990s, quickly disappeared. By jetting distinct volumes (voxels) onto the growing object, it contributed material from all spatial directions [2].

The foundation of layer-based technology is the construction of a 3D physical item called a "part" from several equal-thickness layers. The contours of each layer are determined by the matching 3D data collection, and they are then placed on top of one another.

1.1.3 Additive Manufacturing (AM)

Additive manufacturing (AM) was created using the idea of layer-based technology. It is distinguished by the process chain shown in Figure1.1. The first step is to produce a (virtual) solid 3-D CAD data set that represents the intended component. Engineering frequently collects the data set using 3D CAD design and scanning like computerized tomography scanning.

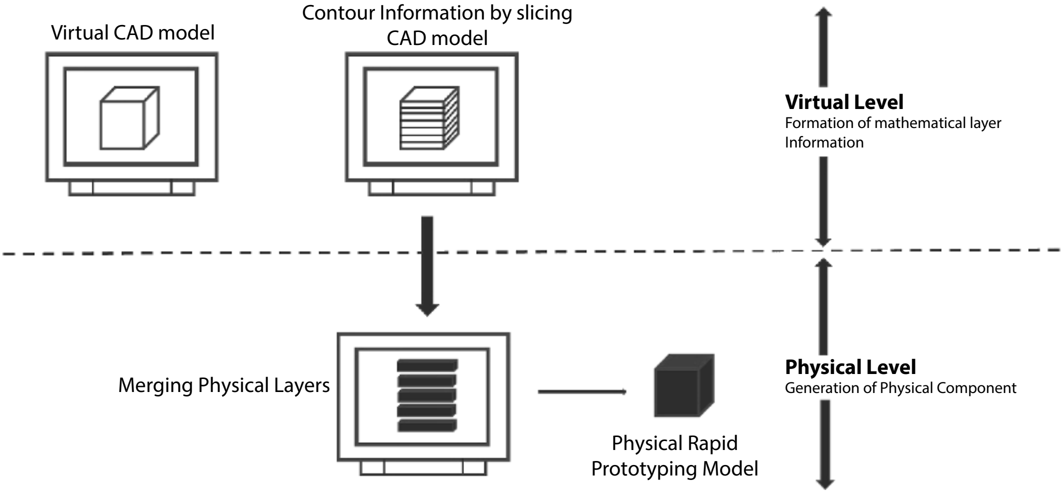

Figure 1.1 Concept of additive manufacturing drawn by a computer.

The 3D data collection is initially divided into layers utilizing a computer and specialized software, regardless of how it was acquired. Consequently, a collection of uniformly thickened contoured virtual slices is produced. The data set, which consists of the layer number (or z-coordinate), the layer thickness (dz), and the contour data (x-y) for each layer, is sent into a machine that performs two simple process steps on each layer to produce the part. Each layer is first handled in accordance with the provided contour and layer thickness information. This can be done in a variety of ways using a variety of physical phenomena. The simplest method is to cut a foil or ready-made sheet into an outline. The top layer of the partially finished sculpture is created in the second stage by connecting each layer to the one below it. The most straightforward technique is to utilize shaped foil and adhere it once more on top of the previous layer. The physical model is constructed layer by layer, starting at the bottom and working its way up to the final piece. The nearly 100 different AM machines that are currently available all share the same underlying procedures, often known as a process chain. Only how each layer is processed and how neighboring layers are connected to make the part differs between the machines [3].

Additive manufacturing (AM) is an industrial method, as a first conclusion:

- A digital product model, which is a 3-D virtual object built solely on a 3D data set.
- Using layers of uniform thickness that have been shaped to match the respective product model cross sections. Thus, AM is essentially a 2.5D process.
- It can be carried out at any stage of the product development process because it does not obstruct the design process.
- That mostly uses proprietary materials, creating a solid relationship between the method, the build material, and the machine. With more machines on the market and more third-party material suppliers interested in entering the market, this influence will wane.

1.2 Application Levels

The AM method is utilized for a limited number of applications, as contrast to another method that is only fit for one application. This viewpoint exhorts people to first examine every process then consider the appropriate applications. The selection of the most appropriate AM method begins with the corresponding application. Then, certain specifications, such as dimensions, temperatures, tolerated mechanical forces, etc., lead to an appropriate material and, ultimately, a machine proficient of effectively managing all these specifications. The same issue can be resolved via a variety of AM procedures.

To begin defining such a structure, it is necessary to distinguish between the definitions of "technology" and "application". Technology, which describes the scientific methodology, is described as the science of the technical process. Application, often known as the practical approach, refers to how to employ technology to your advantage.

Different classifications of applications—referred to as "application levels"—are defined to get a better understanding. Even though there have been efforts to standardize the definitions, they are not yet complete and alternate words are occasionally used. As shown in Figure 1.2, the primary application levels of AM technology—"Rapid Manufacturing and Rapid Prototyping"—define it.

1.2.1 Direct Processes

All AM procedures are referred to as "direct methods" to denote the fact that a generative machine transforms the digital method model clearly into a substantial item known as the part. Some procedures, however, are referred described as indirect rapid prototyping processes." They are not additive manufacturing procedures since they do not use the layer manufacturing principle. Indirect processes are largely mimic silicon rubber casting techniques, such RTV. Because it sounds more creative, the phrase "Indirect Rapid Prototyping Processes" was coined because AM parts are utilized as masters.

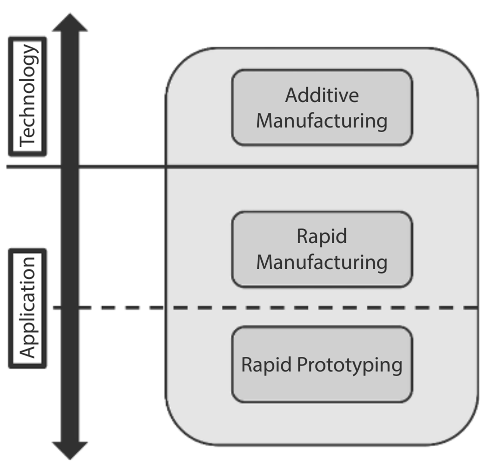

Figure 1.2 Technology and application levels for additive manufacturing.

1.2.1.1 Rapid Prototyping

It is feasible to differentiate between the two sub-levels of the application level "rapid prototyping," namely "Solid Imaging" and "Functional Prototyping" on the one hand, and "Fast Prototyping" on the other hand. Figure 1.3 shows the application of rapid prototyping with sub-level of solid imaging.

Solid imaging or concept modelling describes a family of components used to validate a fundamental idea. The components resemble a statue or a three-dimensional image. They typically can't be loaded. They are just applied to gain a sense of space to assess the overall appearance and proportions. The components are also known as "show-and-tell models" as a result.

Scaled concept models are frequently employed to validate intricate CAD drawings. They are also referred to as "data control models" in this context. Data control includes not just validating CAD data but also serving as a starting point for interdisciplinary talks when they arise, such instance when dealing with packaging issues. Colored models created using the powder-binder method of 3D printing are important resources for idea analysis. The use of color highlights a product's weak points and organizes the conversation. In fact, the section is not colored; nonetheless, the model's various colors can, for example, be related to the agenda's themes. Functional prototyping is used to check and validate one or more distinct functions of the final product or to decide whether to go into production as shown in Figure 1.4.

When a product is still in the very early stages of improvement, the air distribution can be checked using the adjustable air outlet grill for the temperature control nozzle of a passenger car. Using laser stereolithography, it was created in one piece. This procedure produces a surface that is smooth and matches the later series superiority, but owing to its mechanical and particularly thermal qualities, as well as its color and high price, it is not suitable as a series part. One connecting layer within the hinges was left uncured when the moving parts were manufactured. A last stage involved cleaning the completed item and manually removing any uncured material. A redesigned, inexpensive walkie-talkie is the mobile.

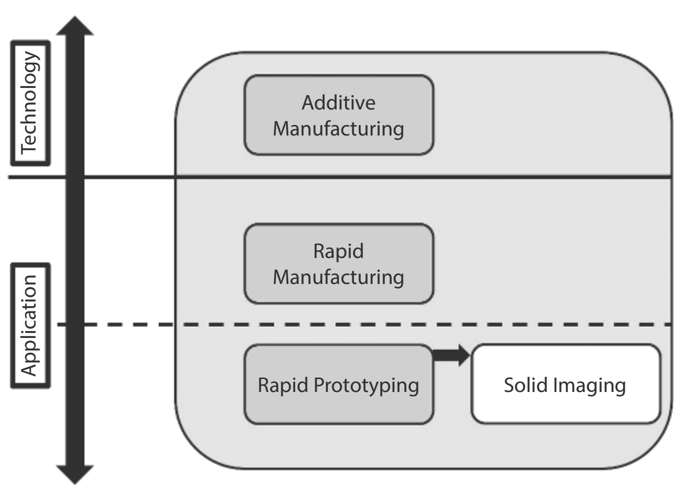

Figure 1.3 Application of rapid prototyping with sub-level of solid imaging.

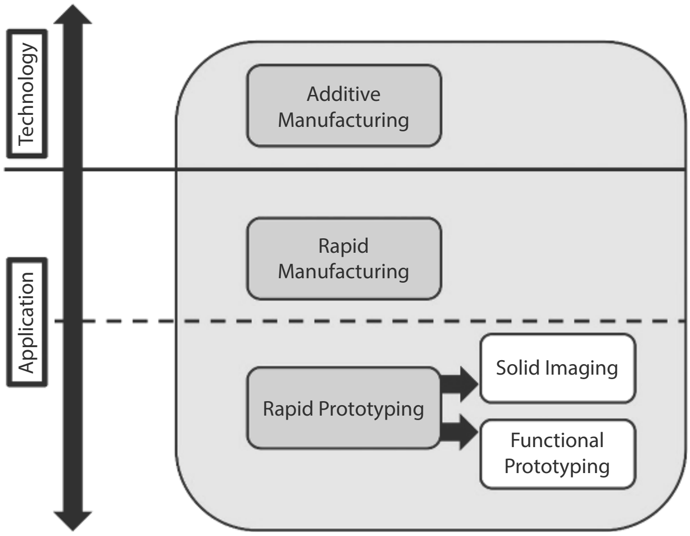

Figure 1.4 Application of rapid prototyping with sub-level of functional prototyping.

Rearranging the speaker and microphone will enable simultaneous speaking and hearing as well as ergonomic handling when using it as a mobile. Using fused deposition modelling, or FDM, ABS polymers are utilized to create the two-piece test housing. The electronics are intended to be held by the lower section, while the housing is covered by the upper element. For evaluation, both components need to fit together exactly. To demonstrate the ideal fit and evaluate the handling, the prototype housing was employed [4].

1.2.1.2 Rapid Manufacturing

The process level "Rapid Manufacturing" covers all operations that produce finished goods or finished components that must be put together to create a finished good. If an AM part demonstrates all the attributes and functionalities assigned to it during the product development process, it is referred to as a product or final part. The method is known as "Direct Manufacturing" if the final product is a positive item, and "Direct Tooling" if it is a negative part, such as a die, Mould, or gauge. Final items produced using Direct Manufacturing originates directly from the AM process (Figure 1.5). The ability to treat a wide range of materials directly utilizing an AM method is now available for all material classes (ceramics, and metals). It is not crucial in this context that the materials on hand exhibit the same physical characteristics as the materials employed in conventional production procedures. But it must be guaranteed that the chosen AM method and material can realize the features on which the engineering design was based.

A three-unit dental bridge manufactured from CoCr-alloy using selective laser sintering (SLM) is shown. A dental impression was used to collect the data from the patient, which was then digitalized. The dental bridge was created using the expert dental software. It was created and immediately produced with SLM. The bridge was prepared for insertion into the patient's mouth after completion and geometric testing [5]. In comparison to conventional methods, the directly built bridge was speedier, perfectly fitted, and more affordable.

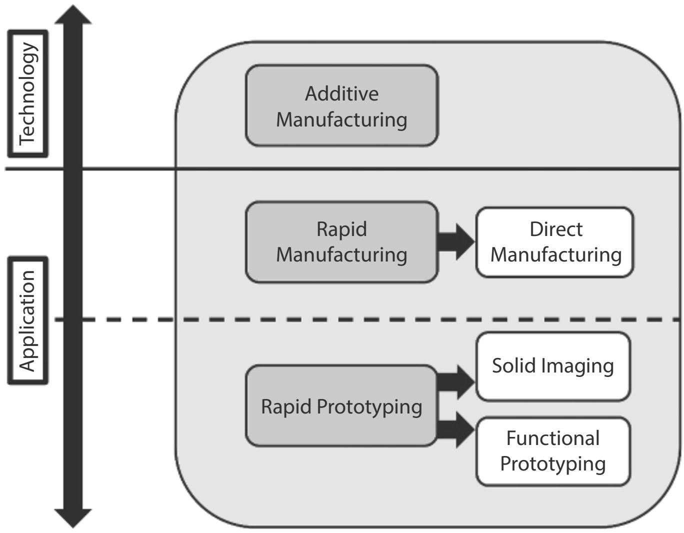

Figure 1.5 Application of rapid manufacturing with sub-level of direct manufacturing.

A hinge for an aeroplane engine cover was redesigned, manufactured directly, and put to the test. A bionic-style design was created that reduced weight by 50%, however it could no longer be produced by milling. It passed the standard tests and performed flawlessly because it was created utilizing the AM metal method of selective laser melting (SLM).

1.2.1.3 Rapid Tooling

All additive manufacturing (AM) processes that result in finished parts utilized as cores, cavities, or inserts for tools, dies, and molds are referred to as rapid tooling. It is necessary to distinguish between direct tooling and prototype tooling as two sub-levels. Technically speaking, direct tooling and direct manufacturing are equal, but direct tooling results in series-quality tool inserts, dies, and molds (Figure 1.6) instead. There are valid reasons to classify tooling as a different application sub-level, even though it is merely based on the inversion of the product data set (from positive to negative). Additionally, a tool construction is required for data inversion, including scaling to account for shrinking, draught angles, and other components. For the most part, tooling requires a metal process and equipment made for it.

It is crucial to realize that "direct tooling" simply refers to the generation of tool components, such as cavities or sliders, and does not indicate that the full tool is created. These cavities and common parts or inserts are used in a conventional tool production procedure to create the overall tool.

AM techniques' layer-based technology enables the creation of internal hollow structures. For instance, internal cooling tubes that match the shape of the hollow beneath the surface can be integrated into mold inserts. The process is known as conformal cooling because the cooling channels are shaped to fit the mold's shape. The output of a plastic injection mould can be greatly boosted because to the increased heat extraction. Additionally, the design of cooling and heating channels might result in an integrated heat management

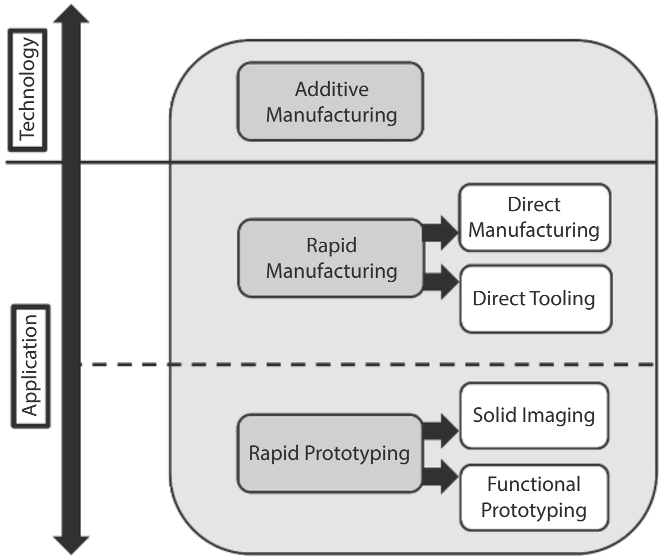

Figure 1.6 Application of rapid manufacturing with sub-level of direct tooling.

system and, consequently, far more powerful tools. High precision is necessary to create a steel blow mould to produce golf balls. The direct metal laser sintering method was used by AM to create a mould that is nearly net-shaped. Although it's not a finished product, it serves as a great illustration of how additive manufacturing and successive high precision machining [6].

Prototyping equipment. For small series manufacturing, a mould of series quality is frequently too expensive and time-consuming. A temporary mould built from a different material usually works well if only a few parts are required, or details are regularly modified. This form of mould exhibits the same quality as working prototypes but at least partially satisfies the requirements for direct tooling application. The related application level is sort of the middle of quick manufacturing and rapid prototyping. "Prototype Tooling" is the name of this level below. Although this nomenclature is also used for subsequent quick prototyping methods, some people refer to it as "rapid tooling. A polyamide prototype tool is shown as an illustration. It is employed to create a small run of a novel grip sole design for rubber boots. Without creating a series-like metal tool in preparation, the soles are required to create the full boot by attaching them to a bootleg that has already been constructed. Even on a tight budget, casting can be used to assess various sole structures and materials extremely fast. Shown is a tool prototype that can be utilized with a plastic injection molding machine. It is produced using a unique form of stereolithography known as AIM (ACES Injection Molding), where ACES is a 3D Systems-exclusive construction method. Using AM stereolithography, both mould halves are created simultaneously. The shapes should ideally have thin walls and be supported by a thermally conductive substance, such as aluminium filled epoxy. AIM is appropriate for simple shaped items that are being injected in modest volumes.

When various tooling types are considered collectively, it becomes clear that "Rapid Tooling" does not denote an independent application level (Figure 1.7). All additive

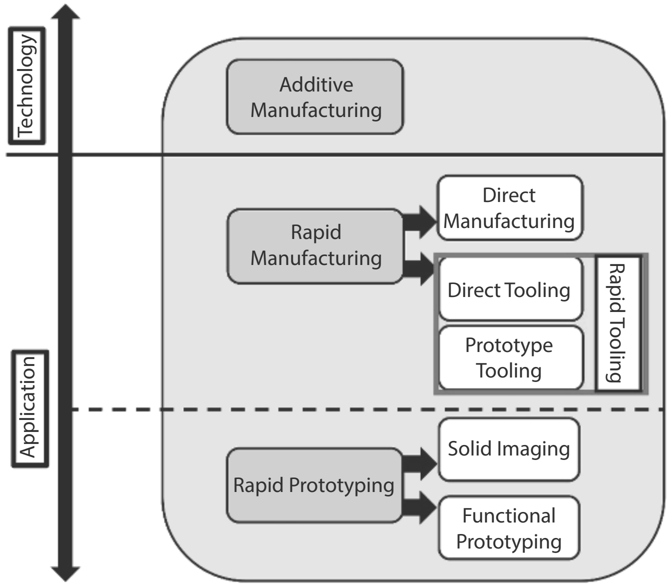

Figure 1.7 Application of rapid tooling.

manufacturing (AM) applications that may create dies, molds, or matching inserts are integrated via rapid tooling.

1.3 Application Levels – Indirect Processes

The AM technique directly produces a physically scaled and geometrically accurate replica of the virtual data set. But there are drawbacks to this method as well. AM procedures

- Work with materials that are dependent on processes, and hence machines, as well as limitations on color, transparency, and flexibility.
- Demonstrate essentially little cost savings as production volume rises.
- When utilized to create many copies, particularly for series applications, are relatively expensive.

AM parts can be utilized as master models for later copying or reproduction procedures to get around these issues. This is based on a concept known as "the splitting of capabilities": The AM technique swiftly produces the exact geometrical portion, while a subsequent replicating procedure provides the needed amount and other qualities like color and so forth.

A copying or follow-up process is not an AM process because it does not use layers. An "Indirect Process" is what it is called. Some refer to it as "Indirect Rapid Prototyping Process" for marketing purposes and to convey the manufacturing speed. For the same reason, the phrase "secondary rapid prototyping process" is occasionally employed in literature.

1.3.1 Indirect Prototyping

If the AM part is unable to accomplish so, indirect prototyping is used to enhance its qualities to satisfy the applicator's needs. For instance, if a flexible item is required but cannot be manufactured directly using an AM method due to material constraints. As a master model for a second or follow-up casting process, a geometrically precise yet rigid AM part is then constructed (and perhaps scaled to account for any shrinkage during casting; see Figure 1.8). Before copying, they need to be manually finished. Since the bulk of the components created through indirect procedures are functional prototypes, they must adhere to the same specifications. Indirect procedures are rarely used to create solid images or concept models since the added time and expense are often not worth it.

There are numerous "secondary processes" that can be applied. The most well-known is "Room Temperature Vulcanization," or RTV for short. It is sometimes referred to as "Vacuum Casting" or "Silicon Rubber Molding." Like silicon rubber molding, many secondary procedures have lengthy cycle durations and are either entirely or partially manual, making them only practical for small series or one-of-a-kind manufacture.

The plug system demands transparent plug housings in a variety of colors. A silicon rubber mould was created utilizing a two-part AM master of the housing as a basis. About 15 distinct copies were produced by the RTV technique using this mould.

Various components were utilized to demonstrate the new product's features to a potential series manufacturer. The system components are not series items even though they work well since they are prototypes produced from prototype material.

The internal assessment of Stefano Giovannio's "Bruce" table lighter, created in 1998, was crucial. It was necessary to handle the lighter with ease and safety since it was used by placing a not reusable lighter into the bottom and blowing the flame out the mouth. The test

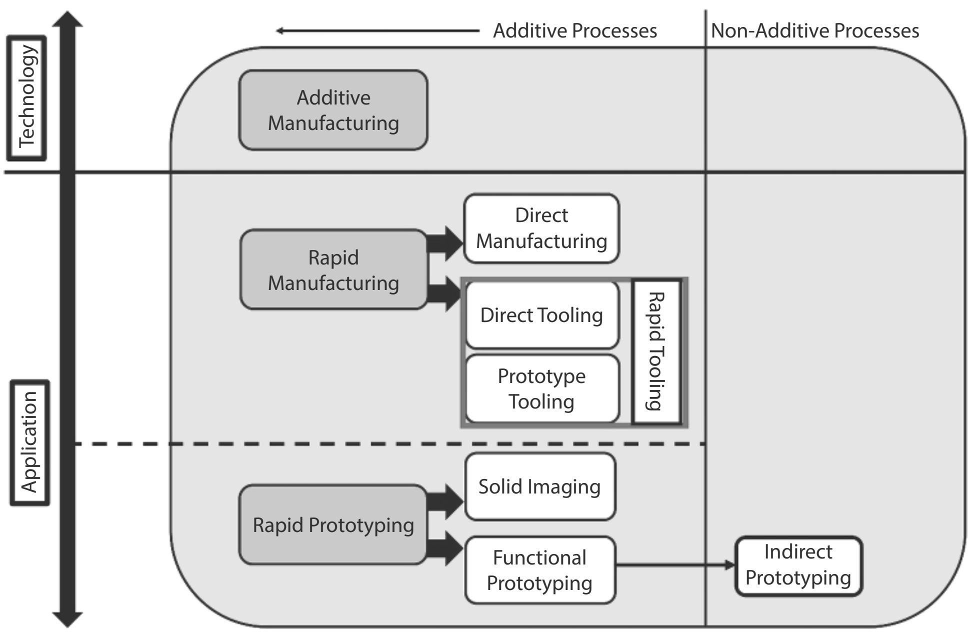

Figure 1.8 Indirect prototyping.

samples were produced by RTV using an AM stereolithography master since steel tooling was costly at this point in the product fabrication process.

Gaskets are one example of a soft material prototype item that frequently has a very complicated shape. This is specifically factual for gaskets used to fix car mirrors, which must serve a variety of purposes, including sealing against water, fixing mirrors and portions of windows, positioning cables, having a pleasing visual appearance, and integrating neighboring extruded sealings [7].

1.3.2 Indirect Tooling

The identical copying techniques used in all indirect processes serve as the foundation for indirect tooling (Figure 1.9). A tool that serves as the foundation for a small or medium-sized batch production of final parts, which is the desired outcome rather than a completed part.

It can be manufactured more quickly and cheaply than series tools produced of tool steel. Like indirect prototyping, indirect tooling avoids milling, grinding, and EDM procedures using AM masters. It must be applicable for more items created from both plastic and metal than silicon rubber molding, in comparison. When viewed from this angle, indirect tooling—which is not a layer-oriented process—can be considered a component of rapid tooling.

An aluminium box and polyurethane counter casting are used to create the mould from an AM master. The mould is applied to perform the necessary quantity of wax pattern once the AM master has been removed. In comparison to a soft silicon mould, a PUR mould produces far more precise wax patterns because of the greater stiffness of the material and the backed-up walls. It is less expensive and has a far shorter lead time than machined

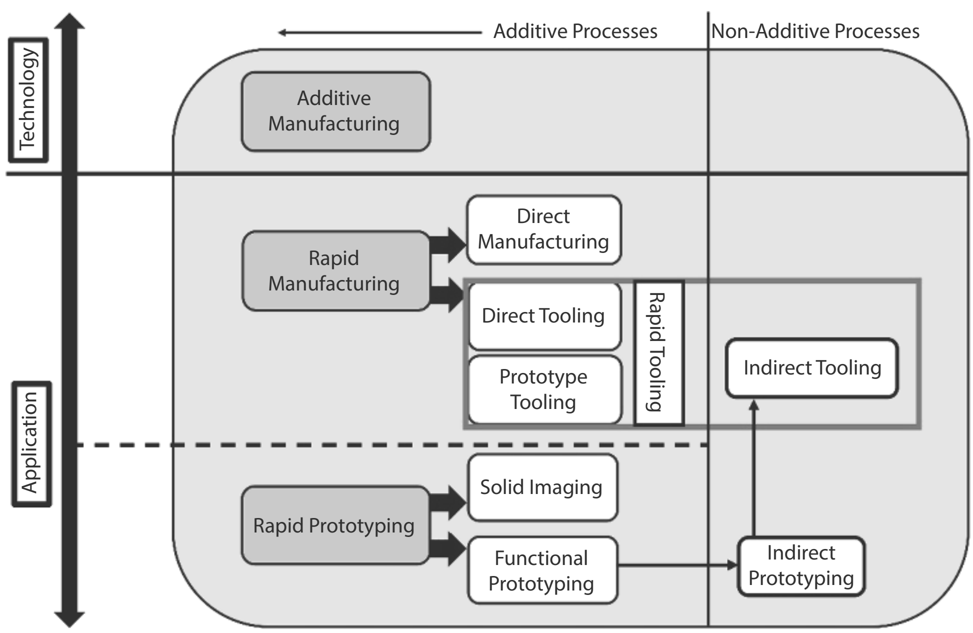

Figure 1.9 Indirect tooling.

all-aluminium tools. This kind of mould can be used to produce intricate precision cast parts in small batches.

Some components cannot be assessed as models built by manual casting from thermoset prototyping material; thus, they must be fabricated using plastic injection molding equipment and from material used in the final series. Plastic components constructed of flame-resistant materials are an example. As a result, rigid molds are required. By employing stereolithography or a polymer jetted master, a suitably stiff mould can be cast from aluminum-filled epoxy without the need for traditional tooling. The procedure is like the RTV procedure not withstanding the material.

Milled inserts may be used to enhance details with sharp edges. Typically, this type of tool does not have cooling, and it only has a few manually driven inserts to replace the sliders. The drawback of lengthy cycle periods must be considered. For testing in a passenger car's engine compartment, a limited number of HD-PE parts have been manufactured [8].

1.3.3 Indirect Manufacturing

On AM masters, too, is implicit production based. The objective is to produce final (or series) parts that have characteristics like conventionally mass-produced goods. Implicit production thus corresponds to the "Manufacturing" product level (Figure 1.10). It was made as a special part based on an AM master made from polystyrene using laser sintering. Evaporative pattern casting is a procedure thoroughly comparable to the lost-wax casting method, was used to convert the scaled master into an aluminium part.

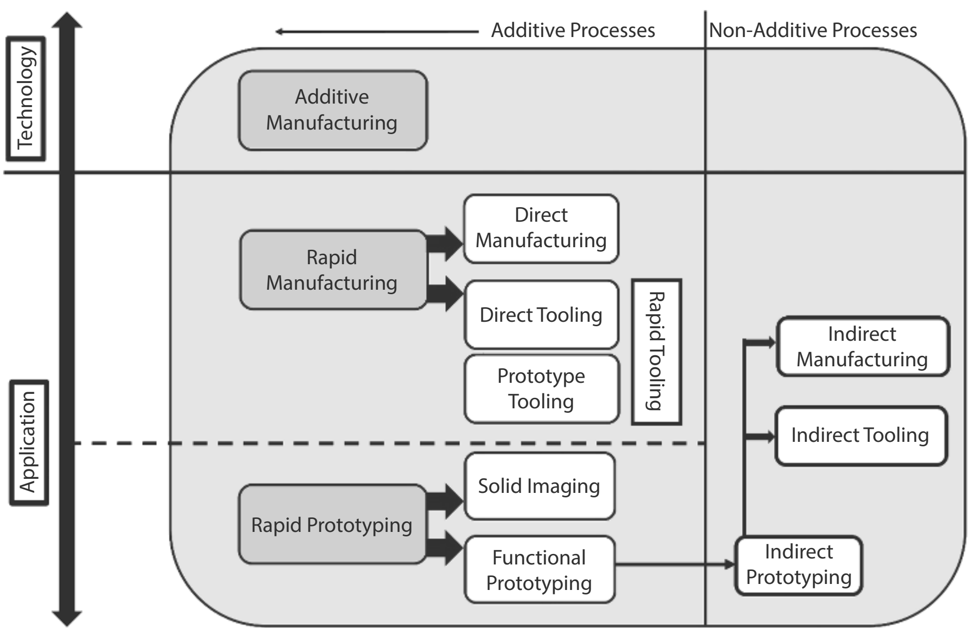

Figure 1.10 Indirect manufacturing.

The result is a collection of identical engine housings. It can be utilized as a small-series product, such as one for racing, as well as to optimize and validate the engine design, including firing test runs long before serial molds are accessible. The question of whether this is an appropriate manufacturing technique is not one of technology but rather of cost.

The air intake manifold of a combustion engine was created using the same procedure. It was cast using lost wax from aluminium. The master was created through polystyrene laser sintering. The cast portion is presented on the right side, and the left part displays the subsequent wax surface treatment.

1.4 Machines for Additive Manufacturing

The market is flooded with several machines for additive manufacturing. They have a shaky connection to the application levels but are largely independent of the employed AM technique.

An apparatus applied for layer-concerned with additive manufacturing is typically referred to as a "fabricator," especially if it can create final items. Some refer to it as a "prototyper" if it can only produce prototypes. The phrase "printer" or "3D printer" is sometimes prefixed with adjectives like "personal," "professional," or other similar ones, and is used to describe all types of layer-oriented additive manufacturing devices.

1.5 Conclusions

The review of additive manufacturing's applications demonstrates that all branches and application levels already profit from AM's capabilities. A professional conversation is supported by the definitions. It is crucial to distinguish between various application levels in practice. Users frequently express their expectations improperly, which leads to disappointments. The examples highlight how different AM processes can be employed, sometimes even in place of one another, to satisfy customer requirements. The several commercially available AM processes are introduced and discussed to take advantage of this characteristic.

The limitations of today, such as a small selection of resources, reduced surface quality, or an excessively slow performing of AM methods, will be soon solved. Numerous enhancements as well as entirely new procedures will be made shortly thanks to the hundreds of industrial product developers and scientists working on all elements of this new technology around the world. Products made of many composite materials will be produced. They will open new markets for industrial goods of all kinds, particularly for electronic components and medical uses.

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