OVERVIEW ABOUT ADDITIVE FABRICATION

Gabriela Georgeta NICHITA
University of Oradea, Romania

Abstract: The success of new industrial product not only depends on its technical features, but also on commercial factors such as cost and the time until the product is laundched on the market. The product variety together with the demand for quality products and a shorter manufacturing and launching time have led to the need of reduced manufacturing series. The different changes in the market requirements entail the necessity of a flexible and efficient manufacturing process.

Keywords: additive fabrication, subtractive processes, layers, digital 3-D model, prototype, part, rapid prototyping, additive technologies, rapid tooling, rapid manufacturing, cost, time, patterns, mold, dies, silicon rubber, processes, selective laser sintering, conventional manufacturing.

1. INTRODUCTION

Additive fabrication refers to a class of manufacturing processes, in which a part is built by adding layers of material upon one another. These processes are inherently different from subtractive processes or consolidation processes. Subtractive processes, such as milling, turning, or drilling, use carefully planned tool movements to cut away material from a workpiece to form the desired part. Consolidation processes, such as casting or molding, use custom designed tooling to solidify material into the desired shape. Additive processes, on the other hand, do not require custom tooling or planned tool movements. Instead, the part is constructed directly from a digital 3-D model created through Computer Aided Design software. The 3D CAD model is converted into many thin layers and the manufacturing equipment uses this geometric data to build each layer sequentially until the part is completed. Due to this approach, additive fabrication is often referred to as layered manufacturing, direct digital manufacturing, or solid freeform fabrication. The most common term for additive fabrication is rapid prototyping. The term "rapid" is used because additive processes are performed much faster than conventional manufacturing processes. The fabrication of a single part may only take a couple hours, or can take a few days depending on the part size and the process. However, processes that require custom tooling, such as a mold, to be designed and built may require several weeks. Subtractive processes, such as machining, can offer more comparable production times, but those times can increase substantially for highly complex parts. The term "prototyping" is used because these additive processes were initially used solely to fabricate prototypes. However, with the improvement of additive technologies, these processes are becoming increasingly capable of high volume production manufacturing, as will be explored in the section on applications. Additive fabrication offers several advantages, listed below:

- *Speed* – as described above, these "rapid" processes have short build times. Also, because no custom tooling must be developed, the lead time in receiving parts is greatly reduced.
- *Part complexity* - because no tooling is required, complex surfaces and internal features can be created directly when building the part. Also, the complexity of a part has little effect on build times, as opposed to other manufacturing processes. In molding and casting processes, part complexity may not affect the cycle times, but can require several weeks to be spent on creating the mold. In machining, complex features directly affect the cycle time and may even require more expensive equipment or fixtures.
- *Material types* - additive fabrication processes are able to produce parts in plastics, metals, ceramics, composites, and even paper with properties similar to wood. Furthermore, some processes can build parts from multiple materials and distribute the material based on the

location in the part.

- *Low-volume production* - Other more conventional processes are not very cost effective for low-volume productions because of high initial costs due to custom tooling and lengthy setup times. Additive fabrication requires minimal setup and builds a part directly from the CAD model, allowing for low per-part costs for low-volume productions.
- *Large parts* - additive processes are best suited for relatively small parts because build times are largely dependent upon part size. A larger part in the X-Y plane will require more time to build each layer and a taller part (in the Z direction) will require more layers to be built. This limitation on part size is not shared by some of the more common manufacturing methods. The cycle times in molding and casting processes are typically controlled by the part thickness, and machining times are dependent upon the material and part complexity. Manufacturing large parts with additive processes is also not ideal due to the current high prices of material for these processes.
- *High accuracy and surface finish* - currently, additive fabrication processes can not match the precision and finishes offered by machining. As a result, parts produced through additive fabrication may require secondary operations depending on their intended use.
- *High-volume production* - while the production capabilities of additive processes are improving with technology, molding and casting are still preferred for high-volume production. At very large quantities, the per-part cost of tooling is insignificant and the cycle times remain shorter than those for additive fabrication. *Material properties* - while additive fabrication can utilize various material types, individual material options are somewhat limited. As a result, materials that offer certain desirable properties may not be available. Also, due to the fabrication methods, the properties of the final part may not meet certain design requirements. Lastly, the current prices for materials used in additive processes are far greater than more commonly used materials for other processes [1], [3], [5].

2. PROCESS STAGES

Several different additive fabrication processes are commercially available or are currently being developed. Each process may use different materials and different techniques for building the layers of a part. However, each] process employs the same basic steps, listed below:

1. *Create CAD model* - for all additive processes, the designer must first use Computer-Aided Design (CAD) software to create a 3-D model of the part.
2. *Convert CAD model into STL model* - each form of CAD software saves the geometric data representing the 3-D model in different ways. However, the STL format has become the standard file format for additive processes. Therefore, CAD files must be converted to this file format. The STL format represents the surfaces of the 3-D model as a set of triangles, storing the coordinates for the vertices and normal directions for each triangle.
3. *Slice STL model into layers* - using specialized software, the user prepares the STL file to be built, first designating the location and orientation of the part in the machine. Part orientation impacts several parameters, including build time, part strength, and accuracy. The software then slices the STL model into very thin layers along the X-Y plane. Each layer will be built upon the previous layer, moving upward in the Z direction.
4. *Build part one layer at a time* - the machine builds the part from the STL model by sequentially forming layers of material on top of previously formed layers. The technique used to build each layer differs greatly amongst the additive process, as does the material being used. Additive processes can use paper, polymers, powdered metals, or metal composites, depending upon the process.
5. *Post-processing of part* - after being built, the part and any supports are removed from the machine. If the part was fabricated from a photosensitive material, it must be cured to attain full strength. Minor cleaning and surface finishing, such as sanding, coating, or painting, can be performed to improve the part's appearance and durability. The process stages is shown in figure 1 (souce of [1]).

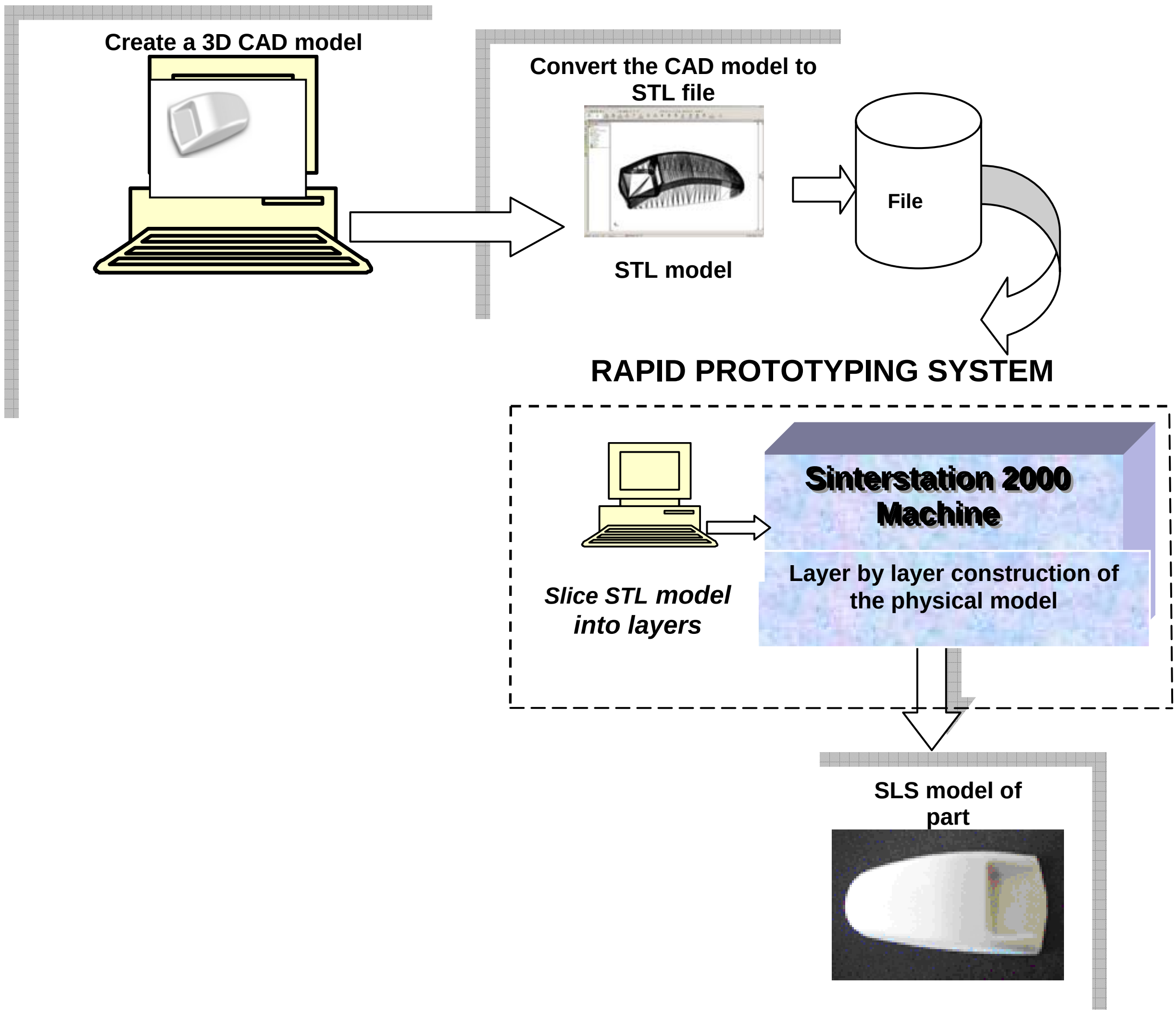

Figure 1. The fabrication process of experimental part, by using Selective Laser Sintering process, source of [1]

3. TECHNOLOGIES USED

The technologies that can be used to build a part one layer at a time are quite varied and in different stages of development. In order to accommodate different materials, as well as improve build times or part strength, numerous technologies have emerged. Some technologies are commercially available methods of fabricating prototypes, others are quickly becoming viable forms of production manufacturing, and newer technologies are continuously being developed. These different methods of additive fabrication, present in table 1, can be classified by the type of material that is employed. Aside from the material type, additive fabrication processes can also be characterized by the number of dimensions of movement that are required to build the part.

For example, a process like Selective Laser Sintering requires movement in the X, Y, and Z directions. In these processes, a laser cures only a small region of a layer at a time. Therefore, the build mechanism (a laser in this case) or the part must move in X and Y direction to allow an entire layer to be formed, and then in the Z direction to allow the next layer to be built. Most additive processes operate in this way, requiring three dimensions of movement. However, some processes may only require two dimensions of movement. Finally, some emerging technologies are using a two dimensional array of mirrors to form an entire part layer at once, requiring movement in only one direction, the Z direction. Such technologies are appealing because fewer dimensions of movement results in faster build times and lower cost [1], [4].

Table 1

❑ ***Liquid-based processes***	These additive technologies typically use photocurable polymer resins and cure selected portions of the resin to form each part layer. The most common liquid-based additive process is Stereolithography (SLA) which was the first commercially available additive process. Parts produced using this technology offer high accuracy and an appearance similar to molded parts. However, photocurable polymers offer somewhat poor mechanical properties which may worsen over time. Other liquid-based processes include Jetted Photopolymer and Ink Jet Printing which may use a single jet or multiple jets.
❑ ***Powder-based processes***	In powder-based processes, such as Selective Laser Sintering (SLS), a selected portion of powdered material is melted or sintered to form each part layer. The use of powdered material enables parts to be fabricated using polymers, metals, or ceramics. *Since being patented in 1989, the Selective Laser Sintering technology has become one of the most utilized processes for prototyping and product development in all industries*. Also, the mechanical properties of these parts are better and more stable than a photocured polymer part. Other powder-based processes include Direct Metal laser Sintering (DMLS) and Three Dimensional Printing (3DP).
❑ ***Solid-based processes***	Solid-based processes use a variety of solid, non-powder, materials and each process differs in how it builds the layers of a part. Most solid-based processes use sheet-stacking methods, in which very thin sheets of material are layered on top of one another and the shape of the layer is cut out. The most common sheet-stacking process is Laminated Object Manufacturing (LOM), which uses thin sheets of paper, but other processes make use of polymer or metal sheets. Other solid-based processes use solid strands of polymer, not sheets, such as Fused Deposition Modeling (FDM) which extrudes and deposits the polymer into layers.

4. APPLICATIONS OF ADDITIVE FABRICATION

Additive fabrication processes initially yielded parts with few applications due to limited material options and mechanical properties. However, improvements to the processing technologies and material options have expanded the possibilities for these layered parts. Now, additive fabrication is used in a variety of industries, including the aerospace, architectural, automotive, consumer product, medical product, and military industries. The application of parts in these industries is quite vast. For example, some parts are merely aesthetic such as jewelry, sculptures, or 3D architectural models. Others are customized to meet the user's personal needs such as specially fitted sports equipment, dental implants, or prosthetic devices. The following three categories are often used to describe the different application of additive fabrication and may be applied to all of the above industries.

- Rapid prototyping - Prototypes for visualization, form/fit testing, and functional testing.
- Rapid tooling - Molds especially and dies fabricated using additive processes.
- Rapid manufacturing - Medium-to-high volume production runs of end-use parts.
- Rapid Prototyping: additive processes are primarily used for the fabrication of prototypes. Initially, this was because the production of end-use products demanded better mechanical properties and lower costs. While these layered parts now offer higher quality and lower costs, other reasons still exist for using additive processes for the fabrication of prototypes. Firstly, prototypes are needed during the design stage and must be produced quickly. Additive processes have short build times and do not require any custom tooling to be created. Secondly,

additive fabrication is more cost effective for low quantities than other processes. Again, this is primarily because no costly tooling is required. The prototypes created through additive fabrication can serve many purposes. The prototype may simply be used for form testing, which is visually assessing the 3D form and design of the part and being able to communicate redesign or manufacturing requirements to other engineers. Prototypes are also frequently used for fit testing, in which the part's compatibility with other components of an assembly can be evaluated. In such form and fit applications, the material and mechanical properties are usually of little concern. Some additive processes produce prototypes used for functional testing, in which the part is tested under the operating conditions of the final product. For this application, the material and mechanical properties are significant and therefore only some additive fabrication processes are used towards this end. By using additive fabrication to produce prototypes, much time and money can be saved in the product design process. The quick fabrication of a prototype means that more designs can be considered and tested in a shorter period of time. Also, potential manufacturing problems that are caused by the part design can be identified before full production begins. Not only does the design process move quicker, but the quality of the design is likely to improve as well [1], [2], [5], [6], [8], [9].

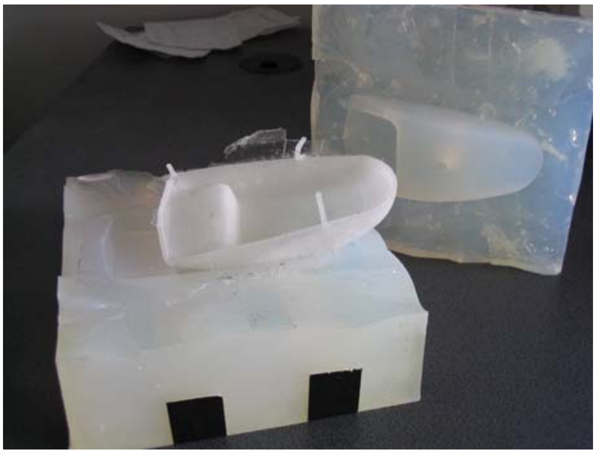

Figure 2. Silicon rubber mold and part obtain by Vaccum casting process, source of [1]

Rapid Tooling: mold especially and dies, the custom tooling for molding and casting processes, are geometrically complex parts that require high accuracy, low surface roughness, and strong mechanical properties. Machining these tools using CNC milling or EDM can be the most time consuming and costly step in the molding or casting process. As a result, using additive fabrication to create the tooling offers a fast and cheap alternative known as rapid tooling. As previously explained, additive fabrication excels at producing highly complex parts without great impact on build time. Also, the highly skilled and expensive labor required to machine a mold is not required. As a result, rapid tooling can enable high-volume production of quality parts without the large initial cost and lead time for the tooling. Rapid tooling also offers the potential for many improvements to the mold design, including complex cooling channels that are more efficient, the use of multiple materials, and functionally grading materials to optimize performance. Some limitations still exist in using rapid tooling. First, additive fabrication does not offer the high accuracy or finishes of machining, so secondary operations are typically required. Also, unlike additive fabrication, machining is able to use hard materials that offer great durability. As a result, rapid tooling is typically only used for low-to-medium volume productions. Lastly, as explained earlier, additive fabrication processes have smaller part size limitations and are unable to produce very large tooling. The most common method of rapid tooling uses additive processes to fabricate the tooling indirectly by first creating a pattern. This pattern is then used to form the mold or die. Patterns are already used in manufacturing processes that use non-permanent molds, such as sand casting and investment casting. In these processes, a pattern is traditionally machined from wood, plastic, or soft metal and used to form the mold. Additive fabrication offers a fast alternative for creating these patterns, which can be re-used many times and offer similar properties to wood or plastic patterns. Indirect tooling from additive fabrication can also be used to form re-usable molds for processes like vacuum casting or injection molding. Vacuum casting can use molds formed by pouring silicon rubber (figure 2, souce of [1]), or room temperature vulcanizing (RTV) rubber around the rapid tooling pattern and allowing it to harden into the shape of the mold. These rubber molds can be used to form up to 50 plastic parts out of various polymers. Rapid tooling patterns can also be used to form metal/ceramic composite molds for injection molding which can produce up to 1,000 plastic parts.

Another type of rapid tooling is direct tooling, which is the use of additive fabrication to directly produce the mold without the need for a pattern. This approach was initially not viable because of the high accuracy and durability required for molds. However, with improvements in additive technologies and materials, direct rapid tooling is now possible. For example, Selective Laser Sintering and Electron Beam Melting have been used to directly fabricate metal molds, capable of producing hundreds of thousands of parts. However, secondary operations are still typically required to improve the finishes and tolerances of the mold.Rapid Manufacturing: another type of rapid tooling is direct tooling, which is the use of additive fabrication to directly produce the mold without the need for a pattern. This approach was initially not viable because of the high accuracy and durability required for molds. However, with improvements in additive technologies and materials, direct rapid tooling is now possible. For example, Selective Laser Sintering and Electron Beam Melting have been used to directly fabricate metal molds, capable of producing hundreds of thousands of parts. However, secondary operations are still typically required to improve the finishes and tolerances of the mold. Rapid manufacturing does have its limitations and is best suited for parts that take advantage of the additive process. As explained earlier, additive technologies excel at producing highly complex geometries, relatively small parts, using multiple materials, and functionally grading materials to improve performance. For parts that are very large, geometrically simple, or require high tolerances and surface finishes, other more conventional processes are still preferred. Assuming that the desired part quality can be achieved, rapid manufacturing can offer many cost benefits over conventional manufacturing. Firstly, additive fabrication does not require any tooling which can be very costly and time consuming to produce for molding and casting processes. Also, additive processes typically have lower labor costs than conventional processes. This is due to the fact that parts are built directly from the CAD model and the process is highly automated. The labor costs are mainly attributed to the setup process, which becomes less significant with higher volume productions.

5. CONCLUSION

Benefits of using Rapid Manufacturing include:

- Eliminating the costly and time-consuming process of tool making by producing parts direct from computer-generated 3D CAD solid models.
- Users add significant speed and flexibility to their production operations with free form fabrication applying additive manufacturing processes.
- Designers are freed from traditional manufacturing processes allowing them to create un-restrictively.
- Finished systems can be completed and deployed faster.
- Design changes can be implemented with total flexibility at any time, with no wasted inventory of obsolete parts and no lag time for expensive and time-consuming tool changes.

REFERENCES

[1] NICHITA Gabriela Georgeta, Theoretical and experimental research regarding by using Rapid Prototyping technologies in manufacturing complex parts, Technical University of Cluj -Napoca, 2004, (in Romanian).

[2] http://manufacturing.kform.com/index.php/investigating-rapid-prototyping.html

[3] http://www.makepartsfast.com/articles/2126/35/Additive-Fabrication-Today

[4] http://louisville.edu/speed/rpc/applications/selective-laser-sintering.html

[5] http://manufacturing.kform.com/index.php/investigating-rapid-prototyping.html

[6] http://www.rapidprototyping.fraunhofer.de/ver2/en/newspr/rapid_tooling.php.

[7] ***, A new system of producing exact and complicated plastic prototype components, 2003,http://www.mcpgroup.co.uk/rpt/rpttvcs.html

[8] ***, MCP Silicone Rubber & Polyurethane Casting Resins, 2003, http://www.mcp-group.co.uk/rpt/rpttmat.html

[9] ***, Your advantages with rapid prototyping and rapidtooling,http://www.hoerdler.de/english/index.htm