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**Abstract**

This chapter discusses how additive manufacturing can be used to develop tooling solutions. Although AM is not well suited to high-volume production in a direct digital manufacturing sense, it does have some benefit when producing volume production tools. This can be from the perspective of using AM to create patterns for parts that are required using materials or properties not currently available using AM or for longer run tooling where AM may be able to simplify the process chain. Commonly referred to as rapid tooling, we discuss here how AM can contribute to the product manufacturing processes.

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**18.1 Introduction**

The term “tooling” refers in this case to the use of AM to create production tools. The tool is therefore an impression, pattern, or mold from which a final part can be taken. There is a variety of different ways in which this can be achieved and these will be discussed in this chapter.

In recent years, as can be seen from other chapters in this book, there has been a tendency to attempt to use AM for production of parts directly from the machine. This is the so-called Direct Digital Manufacture (DDM) and there are numerous reasons why this can be a preferable approach to production. However, there are still a number of reasons for creating tooling rather than DDM:

- The larger the number of parts produced, the more cost-effective it may be to make a production tool, provided it is known how many parts can be made using such a tool.
- The material requirements for the final part may be very specific and not currently available as an AM material but may however be possible through the tooling route.

- It may be that the product developer wants to understand the tooling process and thus use AM to create a prototype tool.
- This may actually be the quickest and most effective way to create the tooling according to the required specifications. This may be particularly relevant where short lead-times are important.

Tooling is often broken up into two types, referred to as “short-run” and “long-run” tooling. Although discussed in numerous articles like those by Pham and Dimov [1], there are no specific definitions for either of these. Therefore we will attempt to distinguish them here.

Short-run tooling may also be referred to as prototype tooling or soft tooling. The objective is to use techniques that achieve a tool quickly, at low cost and with few process stages. Quite often there are a number of manual steps in the process. It is understood that only a few parts are likely to result from use of the tool; possibly even just one or two parts up to around 100 or more. Every time the tool is used, it should be inspected for damage and viability. It may even be possible (or necessary) to repair the tool before it can be used again. It should be noted that if a tooling solution is required in a very short time (say in a few days), then AM-based short-run tooling may be the only way to arrive there.

Long-run tooling has greater emphasis on use of tooling for mass production purposes. Some injection molding tools can last for years and millions of parts. Although wear is always going to occur, the wear-rate is very low due to the relative hardness of the tool compared with the resulting parts that come from them. The processes required to create long-run tools from AM would still be chosen for their relative cost and lead-time, but in this case they are more likely compared with conventional (subtractive) manufacturing processes. Almost every AM-based long-run tooling solution is likely to involve a metal fabrication process.

The benefits of using a rapid tooling solution may be difficult to determine, but could be immense. Very rarely is a product created from a single tool and the more complex the product, the more difficult it is to plan. Consider the problem of bringing a new mass-produced car to the market. Some parts will already be available, some existing parts may require redesigning while others will require design from scratch. Some of these new parts will be relatively simple, while others will have significant performance specifications that could have very long lead-times. Now consider how you would create a plan to bring all these together so that the car is launched on schedule. Even the manufacture of a very simple part could delay the whole process. The use of AM-based short-run and long-run tooling can be extremely beneficial because of the short reaction times and simplified process chains. A car manufacturer may be able to plan more easily and react to disturbances in the process chain more efficiently. Even tooling that does not last very long (or, for that matter, DDM) can be used to bridge the gap to long-term tooling made using conventional methods. Delivery times can be met even though the entire mass production facility has yet to be completed.

The majority of rapid tooling solutions are focused on the creation of injection molding (IM) tooling. This is because there are a huge number of products made

from polymers using this approach. We will go on in this chapter to discuss how we can directly fabricate IM parts using AM as a replacement for subtractive machining processes. Electron discharge machining (EDM) is an alternative to the more conventional abrasive metal cutting that is worth separate consideration in this chapter. Of course, not all products are made from polymer parts. There is a huge variety of metal, ceramic, and composite-based materials and related manufacturing methods. One method that fits very well into an AM process chain is investment casting, which we will discuss here, followed by some less mainstream AM-based approaches that have found niches for some manufacturers.

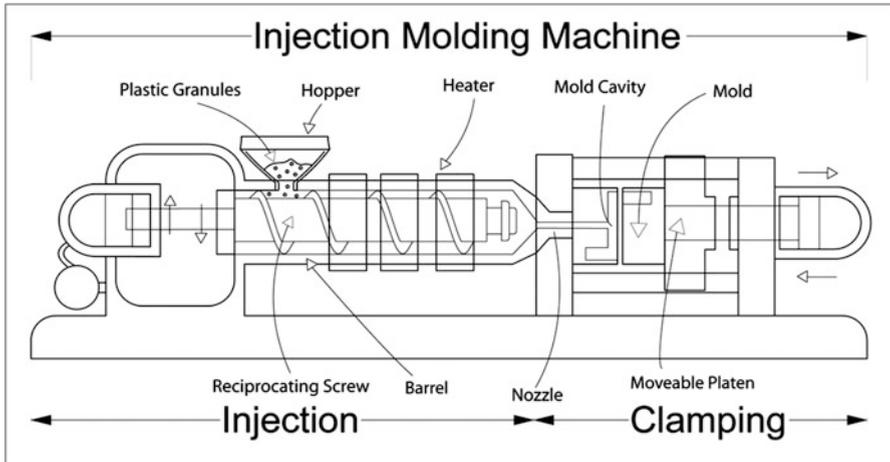
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## 18.2 Direct AM Production of Injection Molding Inserts

Wikipedia describes injection molding as the most common modern method of manufacturing parts and that it is ideal to produce high volumes of the same part [2]. The general principle is quite straightforward in that molten polymer is forced into a metal mold. A simple IM machine diagram can be seen in Fig. 18.1. Once the polymer has cooled and solidified, the mold splits open to reveal the part which is then ejected and the process repeats. There are many texts that cover IM in varying levels of detail. An excellent online resource can be found from Bolur [4]. From these we can see that, similar to many processes, optimization and maximization of the output from IM can be very complex. As our demand for higher throughput, performance, quality, etc. increases so will the need for more cost-effective solutions.

Since the IM process requires a mold that can somehow separate for the part to be removed, there are a number of issues that require attention:

- A simple mold will have a cavity into which the polymer is injected. A core will form the other side of the mold, which is removed after the cooling process so that the part can be ejected. A mechanism (usually a set of ejector pins) is engaged to push the part out from the cavity. However, for this to be effective, the cavity walls usually have a slight slope (referred to as a “draft angle”) that reduces shear forces between the polymer and the mold that would cause the part to stick.
- Not all molds can be easily split into a simple core/cavity to reveal the part. Complex geometry parts may require mold sets that separate into more than two segments. Parts may require very careful redesign so that the number of mold components is minimized. Even so, mold sets can be very complex.
- Filling the mold with molten polymer can also be problematic. The mold must be completely full before it starts to solidify, else there may be cavities. Parts that comprise many features, like thick or thin walls, ribs, bosses, etc. must be carefully analyzed to ensure the mold set is properly filled. Very complex parts may require multiple injection and venting points to ensure effective mold filling as well as fine-tuning of the temperatures, pressures and cycle



**Fig. 18.1** A simple IM machine setup as drawn by Rockey [3]

operations within the IM machine. There are numerous softwares available for mold operation analysis, like Moldflow [5].

As can be seen in Figs. 18.1 and 18.2, an IM machine has a standard plate set into which mold sets are inserted. For these inserts, it is necessary to know where to locate the injection point, the ejector pins, risers, and other features that comprise a fully functioning mold solution. It is these inserts that effectively “customize” the process and where AM can therefore contribute towards a solution.

Inserts can be made using either metal or polymer AM technology. Polymer inserts are obviously less durable, but are much quicker and cheaper to make. In a white paper published by Stratasys, the Polyjet process was demonstrated to be effective for producing inserts for a variety of applications [6]. Figure 18.3 shows Polyjet inserts for a 2-cavity set, with a close-up of the ejector pin arrangement.

IM applications have been tested using the standard Polyjet materials. Best results were presented for the Digital ABS material. Parts were made in a conventional IM machines using a variety of materials, including polyamide, ABS, and polyethylene at temperatures up to 300 °C. Up to 100 cycles have been observed before the inserts broke. Similar results have been reported using SL and polymer laser sintered parts. It is important to note that the IM inserts made this way should be handled carefully so that they can achieve acceptable results. Even though the IM process operates above the heat deflection temperature for the AM materials, it is still possible to get acceptable molded parts. This is possible if the IM cycle is lengthened so that the parts can cool more inside the mold before separation and ejection. Note that this only really works for relatively simple core/cavity sets. For this type of application, the costs can be around half of similar aluminum molds, with significant reductions in lead-time. One can expect some hand-finishing of the resulting molded parts.

**Fig. 18.2** A core/cavity mold set showing a central injection point and channeling to regions where 5 different parts are formed in one cycle



**Fig. 18.3** Polyjet inserts for a two cavity mold set, showing a close-up of the ejector pins (courtesy Stratasys)

The primary concerns when making mold inserts using polymer AM are heat deflection, wear, and accuracy. Most AM processes can provide partial solutions to these problems, but generally the most accurate processes have low heat deflection temperatures and the highest temperature materials can be found in lower accuracy processes. A number of attempts have been made to develop materials for IM inserts with polymer AM processes. One material of note is the copper-polyamide material that was developed for the polymer powder bed fusion process. Adding a copper filler to the polyamide matrix material served to improve the heat transfer away from the surface when a mold is used in the IM machine. The copper also provided additional wear resistance, which increases the life of the mold. It is interesting to note however that this is not a widely used material as the copper-polyamide is not very useful for many other applications so only appropriate where a large number of these molds are needed.

A number of chapters in this book discuss AM of metal parts. One of the initial drivers for this technology was for IM mold inserts. AM can provide a near-net shape for the metal inserts. Several materials have been developed for metal AM that could be used for this, but the most widely used would be H13 tool steel. Almost every process that can achieve this is based on powder metal sintering. Near-net shape can be achieved up to an Ra surface roughness of 12–20  $\mu\text{m}$  but this would generally not be acceptable for most applications and machining of the parting surfaces in particular would be necessary. If the mold surface also requires machine finishing, then very careful attention must be given to gaging so that all of the original part lies outside of the machining volume. Incorrect gaging could lead to some regions not having sufficient stock material to achieve an adequate surface. It is therefore common for designers to add material to the CAD model as a machining allowance. Figure 18.4 shows a tool set where the inserts were made using a powder metal system, with two parts that were molded from them.

Early metal powder AM machines were very expensive and suffered from problems with accuracy and consistent material properties. At that time there were a few alternative approaches to creating metal parts in the Rapid Steel [6] and KelTool [7] processes. While these approaches have become virtually obsolete, there was distinct advantage in that these processes could result in a fully metal part but using a conventional polymer AM machine. However, there was the need for additional furnace technology that added to the expense of the process.

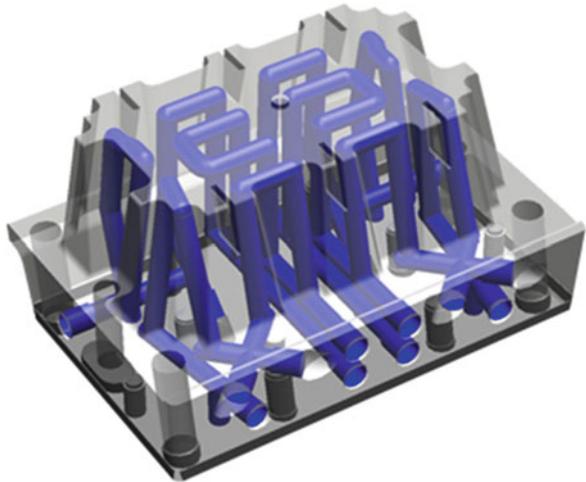
Powder sintering could also be used to create parts that are a blend of polymer and metal powders. The polymeric material acts as a matrix that can hold the metal powder in place. The use of a high thermally conductive metal powder, like copper, would be the most ideal to use for the purpose of creating IM tooling inserts. The copper would cause heat energy to conduct away from the matrix polymer, thus allowing more rapid cooling during the IM process. The copper powder, being harder and more durable than the polymer, would also enable longer tool life.

One significant benefit to the use of AM for creation of injection mold tooling is the capability of creating conformal cooling channels. It is normal to run coolant through the IM inserts, facilitating the cooling of the plastic part following the injection of the molten polymer. This cooling process is very dependent on the geometry of the part being molded, with larger voluminous segments cooling slower than smaller, thinner sections. Greater flow of coolant close to the larger segments can enable faster and more regular cooling, which can also improve the part quality by preventing part warpage due to thermally induced stress. The geometric freedom that is a characteristic of AM can enable very complex cooling channels to be designed into the part. While the best way to achieve such conformal cooling is very much open to debate, benefits have been cataloged [8, 9]. An example of conformal cooling can be seen in Fig. 18.5. Note that this approach can be applied to both short- and long-run methods.

**Fig. 18.4** A direct metal laser sintered tool set, with two parts that have been molded from them



**Fig. 18.5** A tool insert design, showing the location of conformal cooling channels



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## 18.3 EDM Electrodes

A number of attempts have been made to develop EDM electrodes by plating AM parts [10]. These electrodes could feasibly be used for die-sinking EDM for creating cavities for IM application. The most common method of plating the polymer AM parts would be by using electroless plating of copper. There are two major drawbacks to this plating approach. The first is that electroless plating is best suited to plating a thin layer of material on a surface. For EDM however, the electrodes are more effective with a thicker amount of conductive material deposited. It is difficult to deposit sufficiently thick material in a quick and easy manner and with controllable thickness. This leads to the second problem, which is that even if you can deposit sufficient material, the definition of the electrode will be compromised by

this excessively thick layer of material. Although possible, it is not a very effective method of making electrodes.

While it may be possible to create an electrode using powder metallurgy methods from AM molds, possibly a more effective method would be to use direct metal fabrication. Stucker, et al. [11] used this approach to create electrodes using Zirconium diBoride ( $ZrB_2$ ). This material was encapsulated in a copper matrix material, which was melted using a selective laser melting approach. The resulting metal matrix composite was observed to have good erosion characteristics, wearing approximately 1/16th the rate of a pure copper electrode.

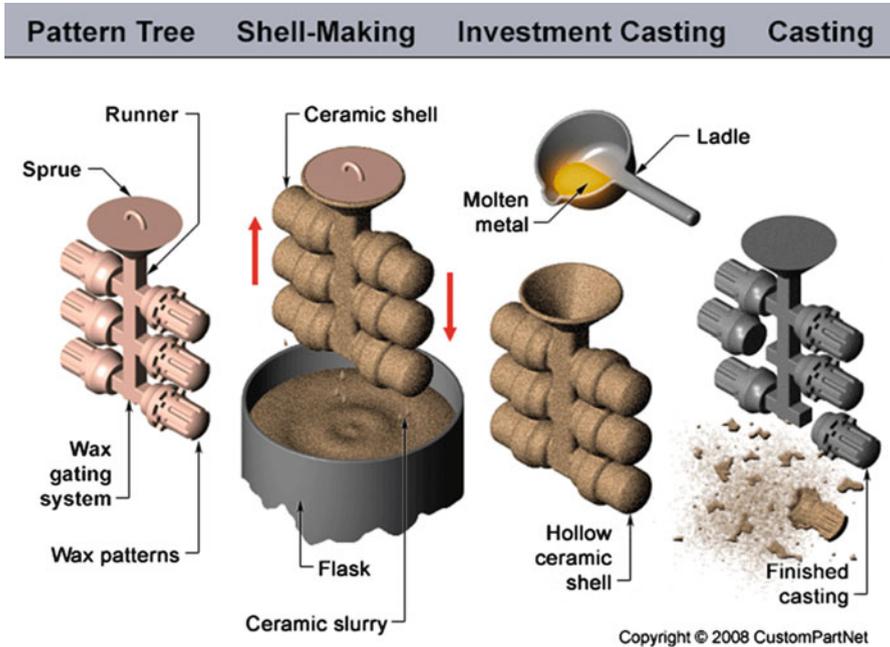
Neither of the above approaches has achieved popularity and there appear to be much better ways of creating EDM electrodes. However, recent improvements in metal powder melting systems may revive this research and development since electrode production can account for a significant amount of the manufacturing costs.

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## 18.4 Investment Casting

Investment casting is the process of generating metal parts from a nonmetal pattern. Figure 18.6 efficiently describes the investment casting process. The patterns are in some way assembled into a structure that can be coated with ceramic to produce a shell. The ceramic starts as a slurry into which the structure, referred to as a “tree” for obvious reasons, is dipped to produce a closely forming skin. Once this has dried, it is strengthened by applying more coats until it is strong enough to withstand the casting process. Prior to casting, the pattern is removed by burning out the material. Care must be taken at this stage to ensure all the material has been burned out of the shell, leaving no residue. The ceramic shell can withstand the high temperature of molten metal during the pouring process, which can then be left to cool before the shell is broken from the tree. The metal replicas of the original pattern are cut from the “trunk” of the structure prior to post-treatment.

The great advantage of this is that parts can be made in a wide range of materials, specific to the application. While powder metal AM systems can produce parts directly in metal, there is a much more limited range of metals available. Furthermore, this is an approach that can result in metal parts from a nonmetal AM technology. A number of AM processes are capable of directly making parts in wax, including material jetting and material extrusion. However, it is also possible to make investment casting patterns from other materials, including polycarbonate and ABS, which are available from a wide range of AM machines. The key is to ensure that the material does not expand rapidly during the burnout process, prior to the metal casting. One way to achieve this is to apply the honeycomb core approach, such as the SL QuickCast build style, rather than using a solid fill.



**Fig. 18.6** Schematic of the investment casting process. Courtesy of CustomPart at [custompartnet.com](http://custompartnet.com)

## 18.5 Other Systems

The main purpose of this chapter is to describe the wide range of ways that AM can be used to enhance your manufacturing processes. While there is a push to using AM for direct digital manufacturing, there are still many products that require mass production and here we can see that AM can still contribute. Although injection molding and investment casting are probably the most widely used applications, there are numerous other approaches that have been considered. Below are a few other examples where AM can be used to help solve manufacturing problems.

### 18.5.1 Vacuum Forming Tools

Vacuum forming is commonly used in packaging, where plastic parts are formed from a flat sheet. A typical example is the clear blister packaging that is commonly used to display consumer products. Other examples include parts that form an outer shell for a product, like a plastic safety helmet for example. After the forming, it is common to cut away the material that surrounds the shaped plastic.

Heat and vacuum are applied when the sheet is placed over a tool, which has holes through which the vacuumed air is extracted. This allows the sheet to conform

to the shape of the tool. If a small number of formed parts are required in a series plastic, then the tool could be fabricated using AM. Locating the vacuum holes would be a straightforward process and can be included during the build. Since the heat is not directly targeted at the tool and with the pressures and other forces not being very high, it is acceptable to use polymeric materials that are commonly used in AM, like ABS or nylon.

### 18.5.2 Paper Pulp Molding Tools

It is becoming quite popular to use paper pulp molding techniques to create packaging. The pulp is made from recycled paper and therefore very environmentally friendly. The forming process is also quite sustainable since it does not require much energy to create the shapes since they are primarily created by pressing out the excess water from the pulp. Again, if the packaging is for small volume part production, AM can be used to create the forming tools. The tools can be created quite quickly using a honeycomb fill to reduce build time, weight, and material costs. Furthermore, features can be included to facilitate the excess water channeling. Figure 18.7 shows a typical mold and part made using this approach.

### 18.5.3 Formwork for Composite Manufacture

Carbon and glass fiber composite is an increasingly popular material used to manufacture high performance items that require significant strength to weight ratios. This is particularly important for vehicles, where the reduction in weight can reduce the energy requirements to move it around. Use of AM can assist in this process, particularly where complex shapes are involved. Use of honeycomb core AM build methods can assist in the creation of lightweight patterns around which fiber reinforced composites can be wound. Alternatively, AM parts can act as molds into which carbon or glass fiber reinforced polymers (CFRP or GFRP) can be placed, either pre-impregnated (prepreg) or by applying the resin later. The AM part can be kept inside the composite part in some cases or the AM pattern can be separated from the composite after the resin curing (hardening) stage. The fact that some AM materials can be dissolved away could be useful at this stage. Figure 18.8 shows some parts that have been developed for constructing high performance UAVs (unmanned air vehicles) using CFRP. The white parts are all made using AM.

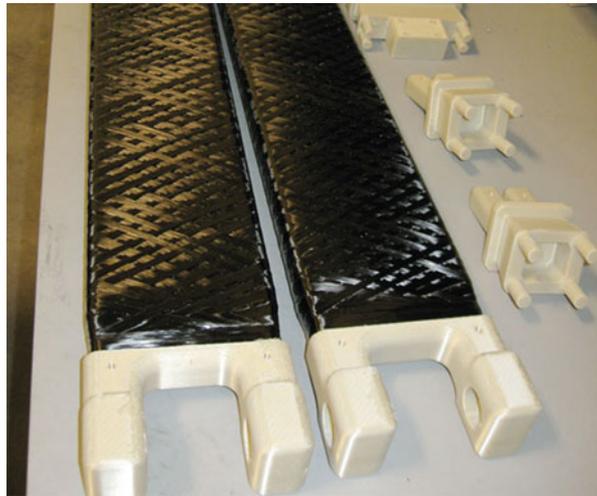
### 18.5.4 Assembly Tools and Metrology Registration Rigs

The majority of products made are assembled in some way from multiple components. Any technique that can simplify or accelerate the assembly process can be extremely beneficial to a mass market manufacturer. We discuss the benefits



**Fig. 18.7** A paper pulp molding tool shown with a molded packaging component (Courtesy of RedEye Redeyeondemand.com)

**Fig. 18.8** Polymer melt extruded AM parts used as formwork for carbon composite manufacture



of DDM in terms of part simplification to reduce the assembly costs elsewhere in this book. However, even for assembly-based manufacture using conventionally made components AM can make a contribution. Some assembly processes benefit from the use of jigs that make it easier to perform the tasks by keeping some of the components in place as well as ensuring that all the components are present, like the example shown in Fig. 18.9. A variation of this approach can be seen with the metrology fixation system produced by Materialise to ensure automotive and



**Fig. 18.9** A hard drive assembly jig (Courtesy of Javelin javelin-tech.com)

similar moldings are kept in place during the metrology process for quality assurance purposes [12].

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## 18.6 Exercises

1. Are there any other reasons for using AM to create tooling other than the 4 mentioned at the beginning of this chapter?
2. What different IM flow analysis software can you find on the Internet?
3. Make a list of the different metal AM technologies that are available. What materials are available for creating IM tooling inserts? Can you find any examples of inserts that have been developed?
4. Find two examples of conformal cooling from the web. Can you identify which method is better? Why is it better?
5. Investigate the manufacture and use of EDM electrodes. What are the potential benefits and pitfalls surrounding the use of AM to directly fabricate these electrodes?
6. There are certainly other examples of mass-manufacturing processes that use AM technology. Build a portfolio of examples and use as a means to discuss how they can benefit in terms of time, cost, ease of use, etc.

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