7.4.8 Design and Fabrication of Custom Prosthesis and Implant

RP can be applied to the design and fabrication of customized prostheses and implants. A prosthesis or implant can be made from anatomical data inputs from imaging systems, e.g., laser scanning and computed tomography (CT). In cases, such as having to produce ear prostheses, a scan profile can be taken of the good ear to create a computer-mirrored exact replica replacement using RP technology. These models can be further refined and processed to create the actual prostheses or implants to be used directly on a patient. The ability to efficiently customize and produce such prostheses and implants is important, as standard sizes are not always an ideal fit for the patient. Also, a less than ideal fit, especially for artificial joints and weight bearing implants, can often result in accumulative problems and damage to the surrounding tissue structures. Case studies on similar applications can be found in Section 7.8.

7.5 APPLICATIONS IN MANUFACTURING AND TOOLING

Central to the theme of rapid tooling is the ability to produce multiple copies of a prototype with functional material properties in short lead-times. Apart from mechanical properties, the material can also include functionalities such as color dyes, transparency, flexibility and the like. Two issues are to be addressed here: tooling proofs and process planning. Tooling proofs refer to getting the tooling right so that there will not be a need to do a tool change during production because of process problems. Process planning is meant for laying down the process plans for the manufacture as well as assembly of the product based on the prototypes produced.

Rapid tooling can be classified into soft or hard, and direct or indirect tooling [3], as schematically shown in Figure 7.3. Soft tooling, typically made of silicon rubber, epoxy resins, low melting point alloys and foundry sands, generally allows for only single casts or for small

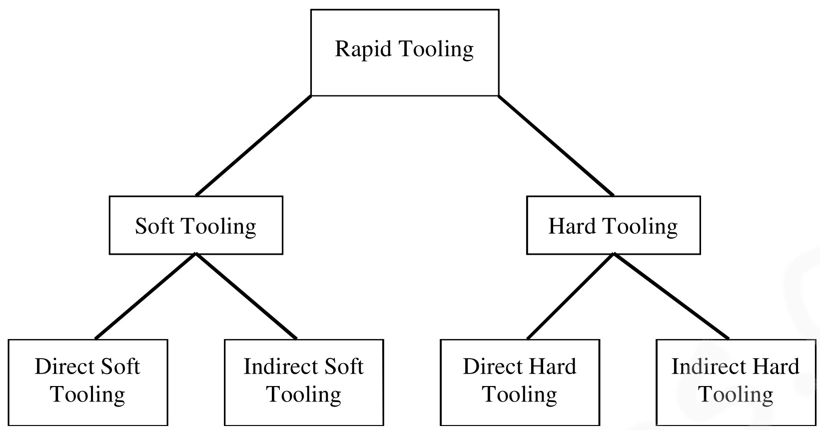


Figure 7.3: Classification of rapid tooling

batch production runs. Hard tooling, on the other hand, usually made from tool steels, generally allows for longer production runs.

Direct tooling is referred to when the tool or die is created directly by the RP process. As an example in the case of injection molding, the main cavity and cores, runner, gating and ejection systems, can be produced directly using the RP process. In indirect tooling, on the other hand, only the master pattern is created using the RP process. A mold, made of silicon rubber, epoxy resin, low melting point metal, or ceramic, is then created from the master pattern.

7.5.1 Direct Soft Tooling

This is where the molding tool is produced directly by the RP systems. Such tooling can be used for liquid metal sand casting, in which the mold is destroyed after a single cast. Other examples, such as composite molds, can be made directly using steoreolithography. These are generally used in the injection molding of plastic components and can withstand up to between 100 to 1000 shots. As these molding tools can typically only support a single cast or small batch production run before breaking down, they are classified as soft tooling. The following section list several examples of direct soft tooling methods.

7.5.1.1 *Selective Laser Sintering® of Sand Casting Molds*

Sand casting molds can be produced directly using the selective laser sintering (SLS®) process. Individual sand grains are coated with a polymeric binder. Laser energy is applied to melt this binder which coats the individual sand grains together, thereby bonding the grains of sand together in the shape of a mold [4]. Accuracy and surface finish of the metal castings produced from such molds are similar to those produced by conventional sand casting methods. Functional prototypes can be produced this way, and should modifications be necessary, a new prototype can be produced within a few days.

7.5.1.2 *Direct AIM*

A rapid tooling method developed by 3D CAD/CAM systems uses the SLA to produce resin molds that allow the direct injection of thermoplastic materials. Known as the Direct AIM (ACES injection molding) [5], this method is able to produce high levels of accuracy. However, build times using this method are relatively slow on the standard stereolithography (SLA) machine. Also, because the mechanical properties of these molds are very low, tool damage can occur during ejection of the part. This is more evident when producing geometrically more complex parts using these molds.

7.5.1.3 *SL Composite Tooling*

This method builds molds with thin shells of resin with the required surface geometry which is then backed-up with aluminum powder-filled epoxy resin to form the rest of the mold tooling [6]. This method is advantageous in that higher mold strengths can be achieved when compared to those produced by the Direct AIM method which builds a solid SLA resin mold. To further improve the thermal conductivity of the mold, aluminum shot can be added to back the thin shell, thus promoting faster build times for the mold tooling. Other advantages of this method include higher thermal conductivity of the mold and lower tool development costs when compared to molds produced by the Direct AIM method.

7.5.2 Indirect Soft Tooling

In this rapid tooling method, a master pattern is first produced using RP. From the master pattern, a mold tooling can be built out of an array of materials such as silicon rubber, epoxy resin, low melting point metals, and ceramics.

7.5.2.1 *Arc Spray Metal Tooling*

Using metal spraying on the RP model, it is possible to create very quickly an injection mold that can be used to mold a limited number of prototype parts. The metal spraying process is operated manually, with a hand-held gun. An electric arc is introduced between two wires, which melts the wires into tiny droplets [7]. Compressed air blows out the droplets in small layers of approximately 0.5 mm of metal.

The master pattern produced by any RP process is mounted onto a base and bolster, which are then layered with a release agent. A coating of metal particles using the arc spray is then applied to the master pattern to produce the female form cavity of the desired tool. Depending on the type of tooling application, a reinforcement backing is selected and applied to the shell. Types of backing materials include filled epoxy resins, low-melting point metal alloys and ceramics. This method of producing soft tooling is cost and lead-time saving. A typical metal spray process for creating an injection mold is shown in Figure 7.4.

7.5.2.2 *Silicon Rubber Molds*

In manufacturing functional plastic, metal and ceramic components, vacuum casting with the silicon rubber mold has been the most flexible rapid tooling process and the most used to date. They have the following advantages:

- Extremely high resolution of master model details can be easily copied to the silicon cavity mold.

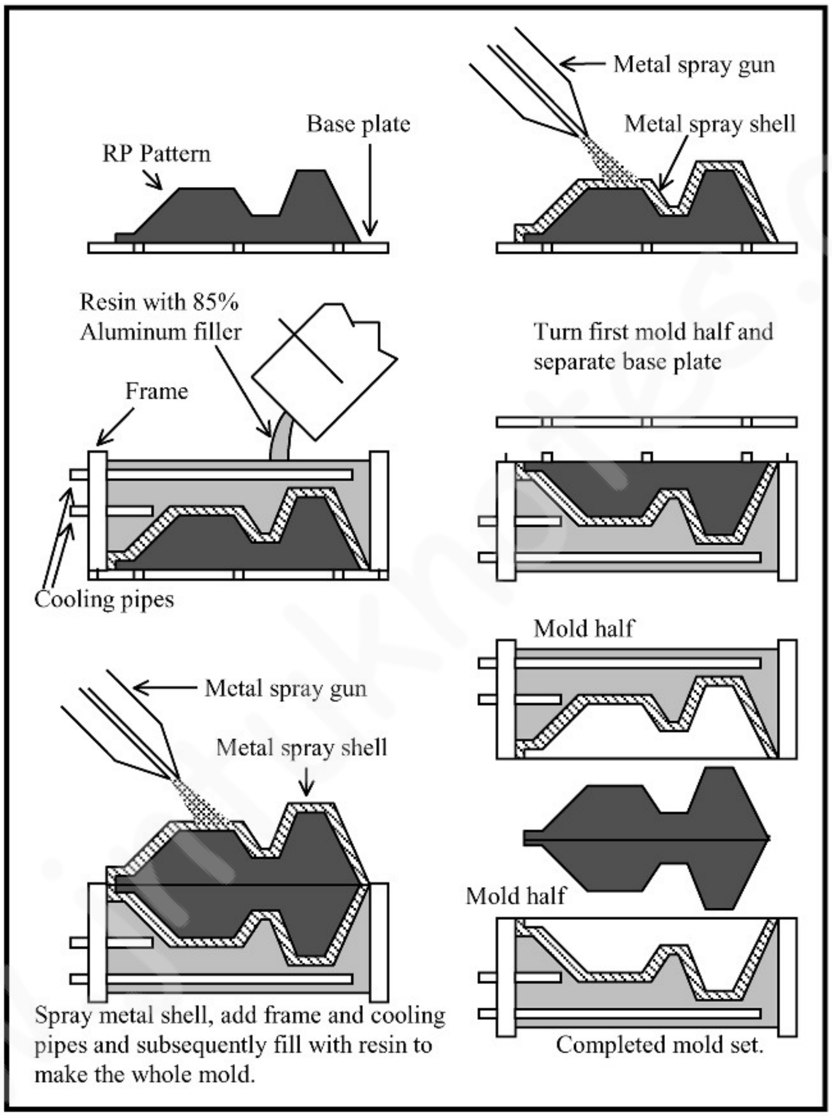


Figure 7.4: A metal arc spray system

- Gross reduction of backdraft problems (i.e., die lock, or the inability to release the part from the mold cavity because some of the geometry is not within the same draw direction as for the rest of the part).

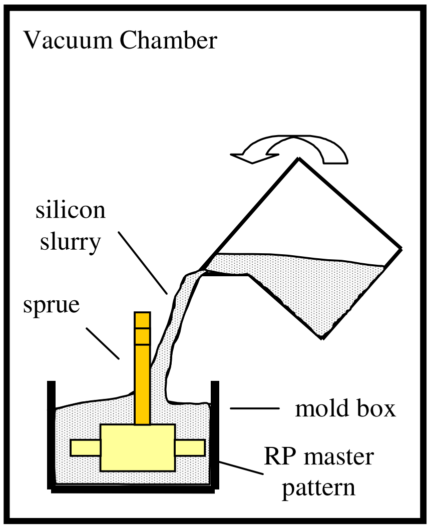
The master pattern, attached with a system of sprue, runner, gating and air vents, is suspended in a container. Silicon rubber slurry is poured into the container engulfing the master pattern. The silicon rubber slurry is baked at 70°C for three hours and upon solidification, a parting line is cut with a scalpel. The master pattern is removed from the mold thus forming the tool cavity. The halves of the mold are then firmly taped together. Materials, such as polyurethane, are poured into the silicon tool cavity under vacuum to avoid asperities caused by entrapped air. Further baking at 70°C for four hours is carried out to cure the cast polymer part. The vacuum casting process is generally used with such molds. Each silicon rubber mold can produce up to 20 polyurethane parts before it begins to break apart [8]. These problems are commonly encountered when using hard molds, making it necessary to have expensive inserts and slides. They can be cumbersome and take a longer time to produce. These are virtually eliminated when the silicon molding process is used.

RP models can be used as master patterns for creating these silicon rubber molds. Figures 7.5(a)–7.5(f) describe the typical process of creating a silicon rubber mold and the subsequent urethane-based part.

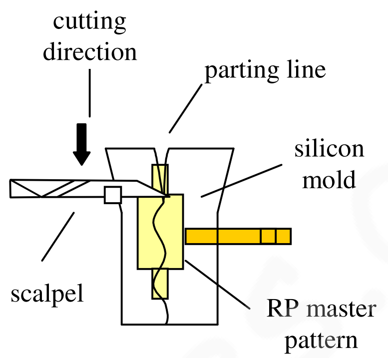
A variant of this is a process developed by Shonan Design Co. Ltd. This process, referred to as the "Temp-less" (temperature-less) process, makes use of similar principles in preparing the silicon mold and casting the liquid polymer except that no baking is necessary to cure the materials. Instead, ultraviolet rays are used for curing of the silicon mold and urethane parts. The advantages this gives is a higher accuracy in replicating the master model because no heat is used, less equipment is required, and it takes only about 30% of the time to produce the parts as compared to the standard silicon molding processes [9].

7.5.2.3 *Spin Casting with Vulcanized Rubber Molds*

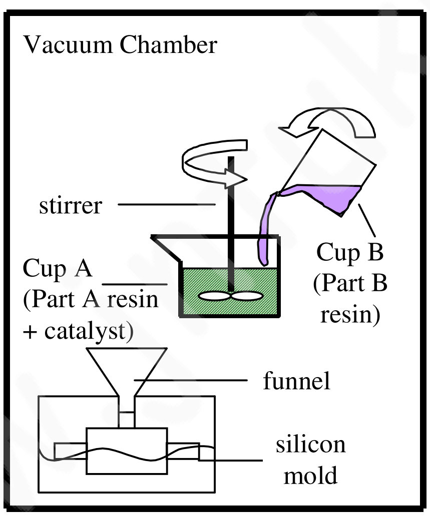
Spin casting, as its name implies, applies spinning techniques to produce sufficient centrifugal forces in order to assist in filling the



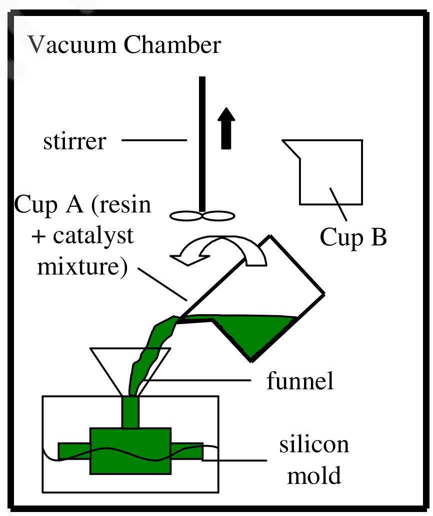
(a) Producing the silicon mold



(b) Removing the RP master pattern

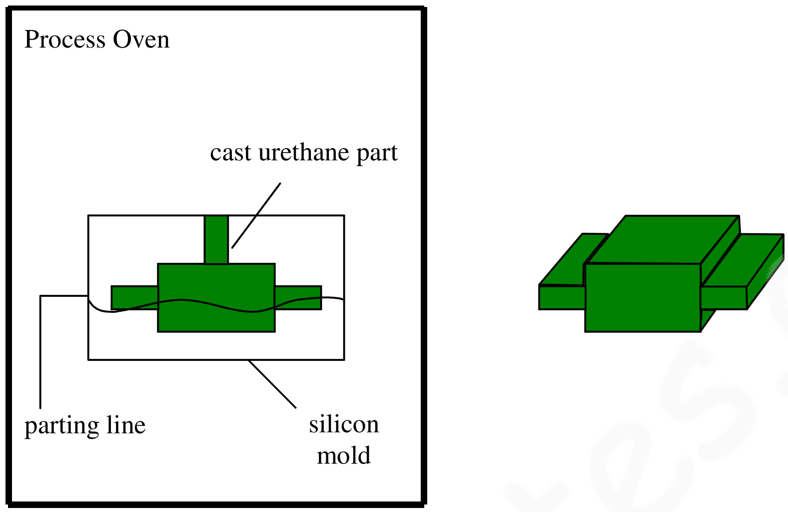


(c) Mixing the resin and catalyst



(d) Casting the polymer mixture

Figure 7.5(a)–(f): Vacuum casting with silicon molding



(e) Cast urethane part cured in a baking oven

(f) The final rapid tooled urethane part

Figure 7.5(a)–(f): (*Continued*)

cavities. Circular tooling molds made from vulcanized rubber are produced in much the same way as in silicon rubber molding. The tooling cavities are formed closer to the outer parameter of the circular mold to increase centrifugal forces. Polyurethane or zinc-based alloys can be cast using this method [10]. This process is particularly suitable for producing low volumes of small zinc prototypes that will ultimately be mass-produced by die-casting.

7.5.2.4 *Castable Resin Molds*

Similar to the silicon rubber molds, the master pattern is placed in a mold box with the parting, line marked out in plasticine [11]. The resin is painted or poured over the master pattern until there is sufficient material for one half of the mold. Different tooling resins may be blended with aluminum powder or pellets so as to provide different mechanical and thermal properties. Such tools are able to withstand up to between 100 to 200 injection molding shots.

7.5.2.5 *Castable Ceramic Molds*

Ceramic materials that are primarily sand-based can be poured over a master pattern to create the mold [12]. The binder systems can vary with the preference of binding properties. For example, in colloidal silicate binders, the water content in the system can be altered to improve shrinkage and castability properties. The ceramic-binder mix can be poured under vacuum conditions and vibrated to improve the packing of the material around the master pattern.

7.5.2.6 *Plaster Molds*

Casting into plaster molds has been used to produce functional prototypes [13]. A silicon rubber mold is first created from the master pattern and a plaster mold is then made from this. Molten metal is then poured into the plaster mold which is broken away once the metal has solidified. Silicon rubber is used as an intermediate stage because the pattern can be easily separated from the plaster mold.

7.5.2.7 *Casting*

In the metal casting process, a metal, usually an alloy, is heated until it is in a molten state, whereupon it is poured into a mold or die that contains a cavity. The cavity will contain the shape of the component or casting to be produced. Although there are numerous casting techniques available, three main processes are discussed here: the conventional sand casting, investment casting, and evaporative casting processes. RP models render themselves well to be the master patterns for the creation of these metal dies.

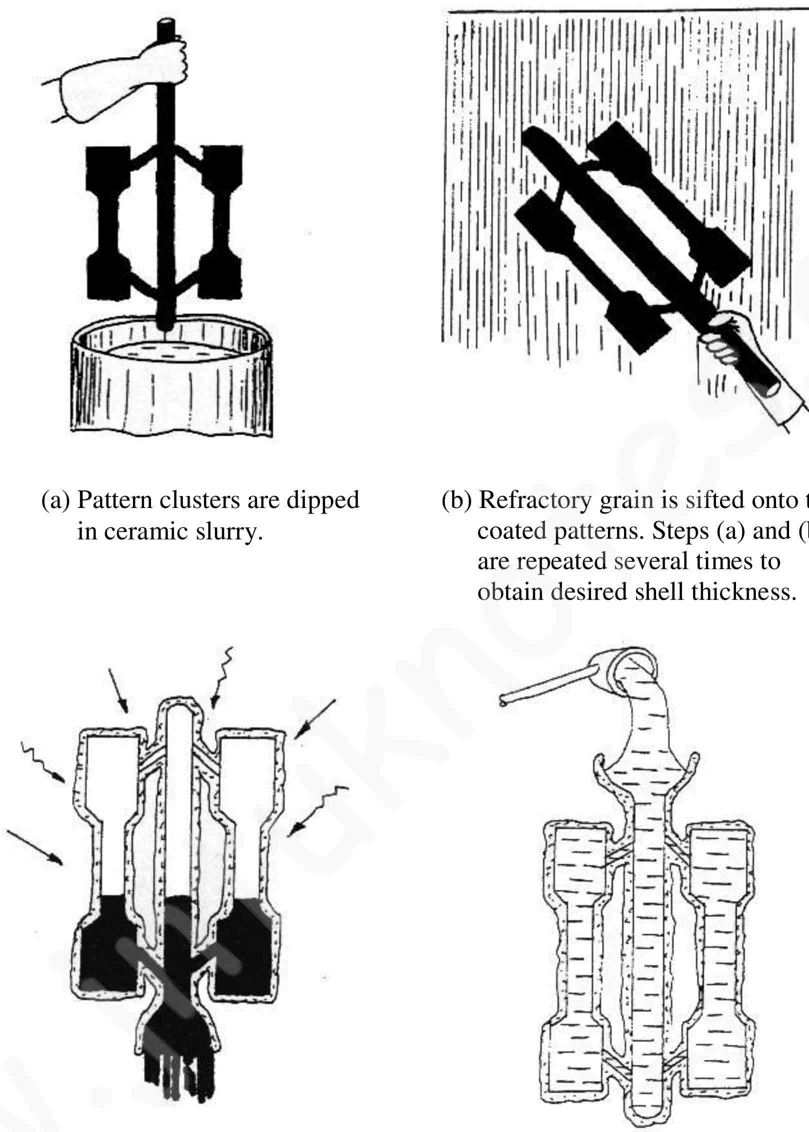
Sand casting molds are similarly created using RP master patterns. RP patterns are first created and placed appropriately in the sand box. Casting sand is then poured and packed very compactly over the pattern. The box (cope and drag) is then separated and the pattern carefully removed leaving behind the cavity. The box is assembled together again and molten metal is cast into the sand mold. Sand casting is the cheapest and most practical method for the casting of

Figure 7.6: Cast metal (left) and RP pattern for sand casting (Courtesy of Helysis Inc.)

large parts. Figure 7.6 shows a cast metal mold resulting from a RP pattern.

Another casting method, the investment casting process, is probably the most important molding process for casting metal. Investment casting molds can be made from RP pattern masters. The pattern is usually wax, foam, paper or other materials that can be easily melted or vaporized. The pattern is dipped in a slurry of ceramic compounds to form a coating, or investment shell, over it [14]. This is repeated until the shell builds up thickness and strength. The shell is then used for casting, with the pattern being melted away or burned out of the shell, resulting in a ceramic cavity. Molten metal can then be poured into the mold to form the object. The shell is then cracked open to release the desired object in the mold. The investment casting process is ideal for casting miniature parts with thin sections and complex features. Figure 7.7 schematically shows the investment casting process from a RP-produced wax master pattern while Figure 7.8 shows an investment casting mold resulting from a RP pattern.

The third casting process discussed in this book is the evaporative pattern casting. As its names implies, it uses an evaporative pattern, such as polystyrene foam, as the master pattern. This pattern can be produced using the selective laser sintering (SLS) process along with the CastForm™ polystyrene material. The master pattern is attached to



(a) Pattern clusters are dipped in ceramic slurry.

(b) Refractory grain is sifted onto the coated patterns. Steps (a) and (b) are repeated several times to obtain desired shell thickness.

(c) After the mold material has set and dried, the patterns are melted out of the mold.

(d) Hot molds are filled with metal by gravity, pressure vacuum, or centrifugal force.

Figure 7.7: Schematic diagram of the shell investment casting process

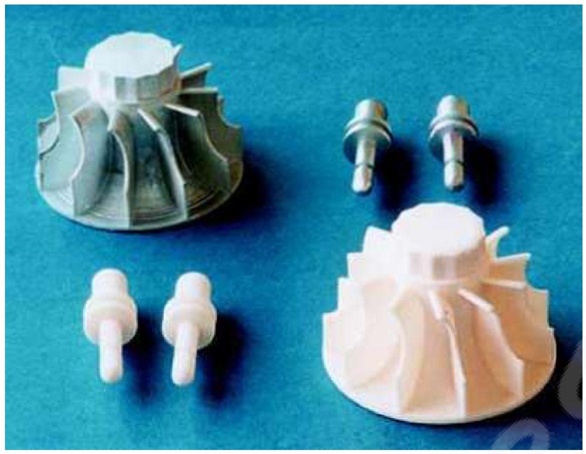
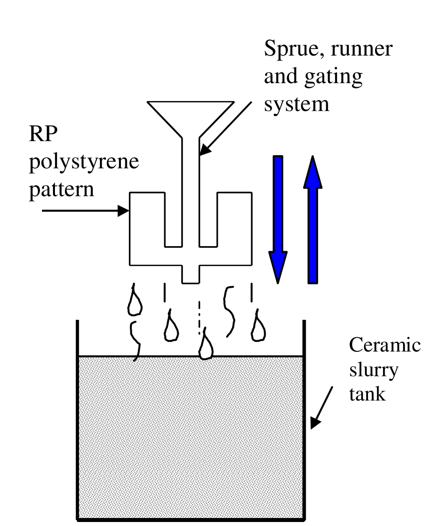


Figure 7.8: Investment casting of fan impeller from RP pattern

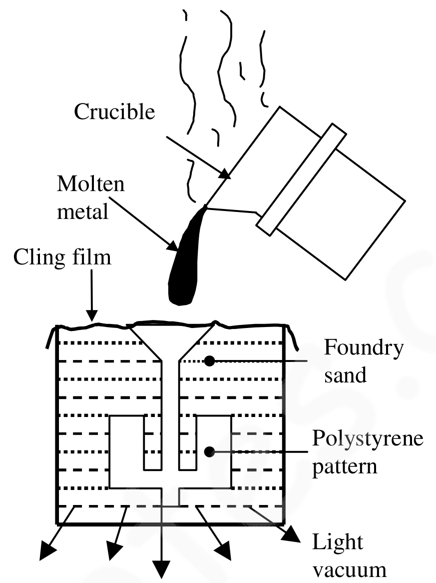
sprue, riser and gating systems to form a "tree". This polystyrene "tree" is then surrounded by foundry sand in a container and vacuum compacted to form a mold. Molten steel is then poured into the container through the sprue. As the metal fills the cavity, the polystyrene evaporates with a very low ash content [15]. The part is cooled before the casting is removed. A variety of metals, such as titanium, steel, aluminum, magnesium and zinc can be cast using this method. Figure 7.9 shows schematically how an RP master pattern is used with the evaporative pattern casting process.

7.5.3 Direct Hard Tooling

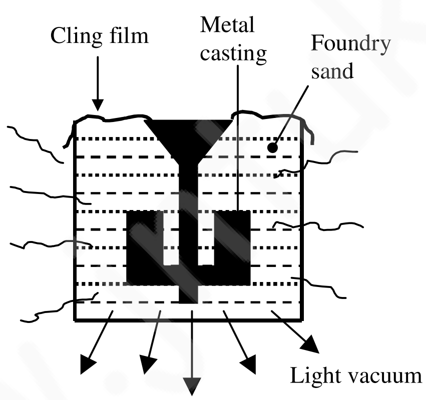
Hard tooling produced by RP systems has been a major topic for research in recent years. Although several methods have been demonstrated, much research is still being carried out in this area. The advantages of hard tooling produced by RP methods are fast turnaround times to create highly complex-shaped mold tooling for high volume production. The fast response to modifications in generic designs can be almost immediate. The following are some examples of direct hard tooling methods.



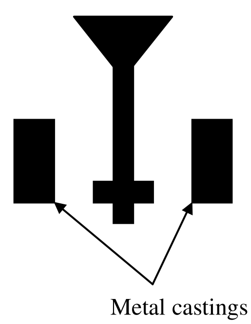
(a) Polystyrene RP pattern "tree" is coated by dipping with a ceramic slurry and air-dried.



(b) Coated RP pattern is packed with foundry sand in a container. The container is sealed with cling film and vacuumed to compact the sand further.



(c) The polystyrene pattern evaporates as the molten metal is cast into the mold. The casting is then left to cool.



(d) After solidification, the final cast parts are removed from the sprue, runner and gating system.

Figure 7.9: Evaporation pattern casting process

7.5.3.1 *RapidTool™*

RapidTool™ is a technology invented by DTM Corporation to produce metal molds for plastic injection molding directly from the SLS Sinterstation. The molds are capable of being used in conventional injection molding machines to mold the final product with the functional material [16]. The CAD data is fed into the Sinterstation™ which bonds polymeric binder coated metal beads together using the Selective Laser Sintering (SLS) process. Next, debinding takes place and the green part is cured and infiltrated with copper to make it solid. The furnace cycle is about 40 hours with the finished part having similar properties equivalent to aluminum. The finished mold can be easily machined. Shrinkage is reported to be no more than 2%, which is compensated for in the software.

Typical time frames allow relatively complex molds to be produced in two weeks as compared to 6 to 12 weeks using conventional techniques. The finished mold is capable of producing up to tens of thousands injection-molded parts before breaking down.

7.5.3.2 *Laminated Metal Tooling*

This is another method that may prove promising for RT applications. The process applies metal laminated sheets with the Laminated Object Manufacturing (LOM) method. The sheets can be made of steel or any other material which can be cut by the appropriate means, for example by CO_2 laser, water jet, or milling, based on the LOM principle [17]. The CAD 3D data provides the sliced 2D information for cutting the sheets layer by layer. However, instead of bonding each layer as it is cut, the layers are all assembled after cutting and either bolted or bonded together.

7.5.3.3 *Direct Metal Laser Sintering (DMLS) Tooling*

The Direct Metal Laser Sintering (DMLS) technology was developed by EOS. The process uses a very high-powered laser to sinter metal powders directly. The powders available for use by this technology are the bronze-based and steel-based materials. Bronze is used for applications where strength requirements are not crucial. Upon sintering of the bronze powder, an organic resin, such as epoxy, is used to infiltrate the part. For steel powders, the process is capable of producing direct steel parts of up to 95% density so that further infiltration is not required. Several direct applications produced with this technology including mold inserts and other metal parts [18].

7.5.3.4 *ProMetal™ Rapid Tooling*

Based on MIT's Three Dimensional Printing (3DP) process, the ProMetal™ Rapid Tooling System is capable of creating steel parts for tooling of plastic injection molding parts, lost foam patterns and vacuum forming. This technology uses an electrostatic ink jet print head to eject liquid binders onto the powder, selectively hardening slices of an object a layer at a time. A fresh coat of metal powder is spread on top and the process repeats until the part is completed. The loose powder act as supports for the object to be built. The RP part is then infiltrated at furnace temperatures with a secondary metal to achieve full density. Toolings produced by this technology for use in injection molding have reported withstanding pressures up to 30 000 psi (200 MPa) and surviving 100 000 shots of glass-filled nylon [19].

7.5.4 Indirect Hard Tooling

There are numerous indirect RP tooling methods that fall under this category and this number continues to grow. However, many of these processes remain largely similar in nature except for small differences, e.g., binder system formulations or type of system used. Processes include the Rapid Solidification Process (RSP), Ford's (UK) Sprayform, Cast Kirksite Tooling, CEMCOM's Chemically Bonded Ceramics (CBC) and Swift Technologies Ltd. "SwiftTool", just to name a few. This section will only cover selected processes that can also be said to generalize all the other methods under this category. In general, indirect methods for producing hard tools for plastic injection molding generally make use of casting of liquid metals or steel powders in a binder system. For the latter, debinding, sintering and infiltration with a secondary material are usually carried out as post-processes.

7.5.4.1 *3D Keltool*

The 3D Keltool process has been developed by 3D Systems to produce a mold in fused powdered steel [20]. The process uses a SLA model of the tool for the final part that is finished to a high quality by sanding and polishing. The model is placed in a container where silicon rubber is poured around it to make a soft silicon rubber mold that replicates the female cavity of the SLA model. This is then placed in a box and then silicon rubber is poured around it to produce a replica copy of the SLA model in silicon rubber. This silicon rubber is then placed in a box and a proprietary mixture of metal particles, such as tool steel, and a binder material is poured around it, cured and separated from the silicon rubber model. This is then fired to eliminate the binder and sinter the green metal particles together. The sintered part which is about 70% steel and 30% void is then infiltrated with copper to give a solid mold, which can be used in injection molding.

An alternative to this process is described as the reverse generation process. This uses a positive SLA master pattern of the mold and requires one step less. This process claims that the CAD solid model to injection-molded production part can be completed in four to six weeks. Cost savings of around 25% to 40% can be achieved when compared to that of conventional machined steel tools.

7.5.4.2 *EDM Electrodes*

A method successfully tested in research laboratories but so far not widely applied in industry is the possible manufacturing of copper electrodes for EDM (Electro-Discharge Machining) processes using RP technology. To create the electrode, the RP-created part is used to create a master for the electrode. An abrading die is created from the master by making a cast using an epoxy resin with an abrasive component. The resulting die is then used to abrade the electrode. A specific advantage of the SLS procedure (see Section 5.1) is the possible usage of other materials. Using copper in the SLS process, it is possible to quickly and affordably generate the electrodes used in electrode EDM.

7.5.4.3 *Ecotool*

This is a development between the Danish Technological Institute (DTI) in Copenhagen, Denmark, and the TNO Institute of Industrial Technology of Delft in Holland. The process uses a new type of powder material with a binder system to rapidly produce tools from RP models. However, as its name implies, the binder is friendly to the environment in that it uses a water-soluble base. An RP master pattern is used and a parting line block is produced. The metal powder-binder mixture is then poured over the pattern and parting block and left to cure for an hour at room temperature. The process is repeated to produce the second half of the mold in the same way. The pattern is then removed and the mold baked in a microwave oven.

7.5.4.4 *Copy Milling*

Although not broadly applied nowadays, RP master patterns can be provided by manufacturers to their vendors for use in copy milling, especially if the vendor for the required parts is small and does not have the more expensive but accurate CNC machines. In addition, the principle of generating master models only when necessary, allows some storage space to be saved. The limitation of this process is that only simple geometrical shapes can be made.

7.6 AEROSPACE INDUSTRY

With the various advantages that RP technologies promise, it is only natural that high value-added industries like the aerospace industry have taken special interest in it even though initial investment costs may be high. There are abundant examples of the use of RP technology in the aerospace industry. The following are a few examples.