UNIT-6

R.P APPLICATIONS

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.

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.

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].

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].

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.

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.

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.

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.

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.

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.

Design Verification of an Airline Electrical Generator

Sundstrand Aerospace, which manufactures inline electrical generators for military and commercial aircraft, needed to verify its design of an integrated drive generator for a large jetliner [21]. It decided to use Helisys's LOM to create the design-verification model. The generator is made up of an external housing and about 1200 internal parts. Each half of the housing measures about 610 mm in diameter and 300 mm tall and has many intricate internal cavities into which the sub-assemblies must fit.

Such complex designs are difficult to visualize from two-dimensional drawings. A physical model of the generator housing and many of its internal components is a good way to identify design problems before the expensive tooling process. But the time and expense needed to construct the models by traditional means are prohibitive. Thus Sundstrand decided to turn to RP technologies. Initial designs for the generator housing and internal sub-assemblies were completed on a CAD system and the subsequent STL files were sent to a service bureau. Within two weeks, Sundstrand was able to receive the parts from the service bureau and began its own design verification.

Sundstrand assembled the various parts and examined them for form, fit, and limit function. Clearances and interferences between the housing and the many sub-assemblies were checked. After the initial inspection, several problematic areas were found which would have otherwise been missed. These were corrected and incorporated into the CAD design, and in some cases, new RP models were made. Apart from design verification, Sundstrand was able to use the physical models to help toolmakers plan and design casting patterns. The models were also used for manufacturing process design, tool checking, and assembly sequence design. Though the approximate cost for the RP models was US$16 500, the savings realized from removing engineering and design changes were immeasurable, and the time saved (estimated to be about eight to ten weeks). was significant.

Engine Components for Fanjet Engine

In an effort to reduce the developmental time of a new engine, AlliedSignal Aerospace used 3D Systems' QuickCast™ to produce a turbofan jet engine for a business aviation jet [22]. Basically, RP is used for the generation of the casting pattern of an impeller compressor shroud engine component. This part is the static component that provides the seal for the high-pressure compressor in the engine. Three different designs were required for testing the cold rig, hot rig and first engine. Using QuickCast™, the 3D Technology Center was able to directly produce patterns for investment castings using the stereolithography technology. The patterns produced were durable, had improved accuracy, good surface finish and were single large piece patterns. In fact, the patterns created were accurate enough that a design revision error in the assembly fixture was easily detected and corrected. With the use of these RP techniques, production time was slashed by eight to ten weeks, and a savings of US$50 000 for tooling in the three design iterations was realized.

Prototyping Air Inlet Housing for Gas Turbine Engine

Sundstrand Power Systems, a manufacturer of auxiliary engines for military and commercial aircraft, needed prototypes of an air inlet housing for a new gas turbine engine [23, 24]. It first needed mock-ups of the complex design, and also several fully functional prototypes to test on the development engines. The part, which measures about 250 mm in height and 300 mm in diameter, has wall thickness as thin as 1.5 mm (see Figure 7.10). It would have been difficult and costly to build using traditional methods.

To realize the part, Sundstrand used DTM's SLS® system (see Section 5.1) at a service bureau to build the evaluation models of the housing and then generate the necessary patterns for investment casting, ultimately the method used for the manufacture. The SLS® system is

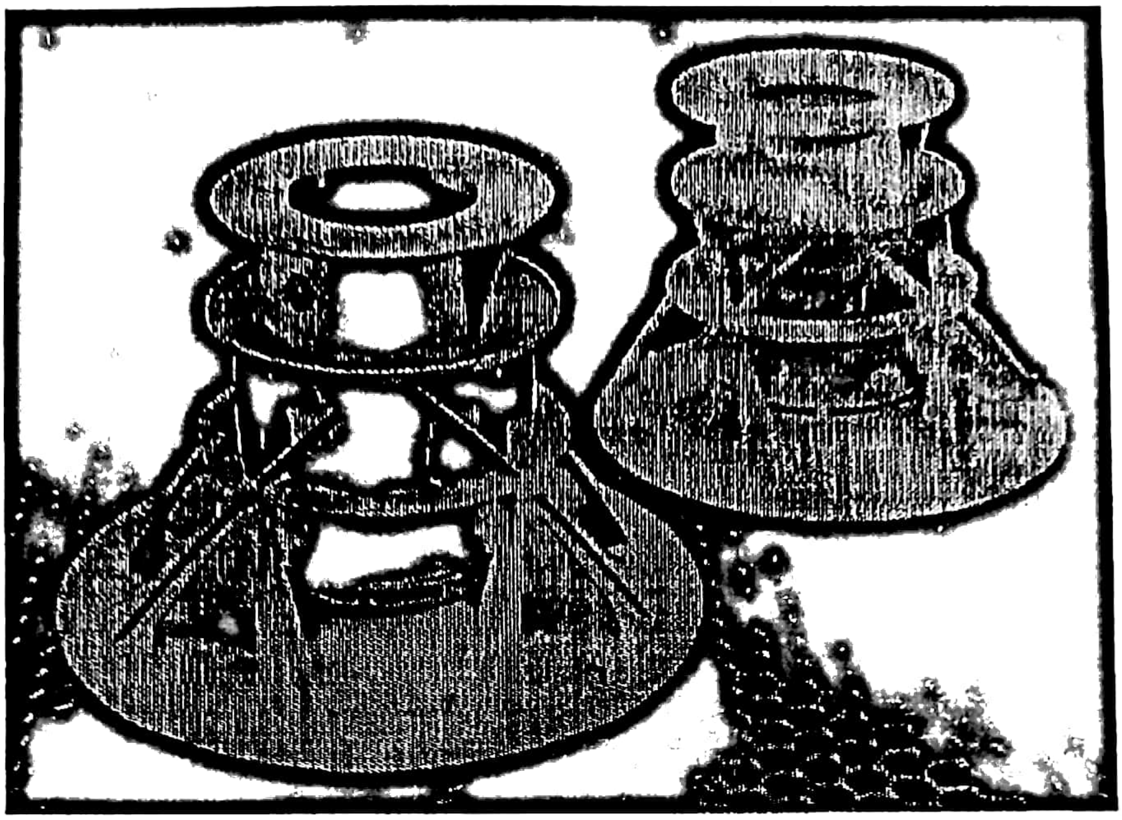

Figure 7.10: Polycarbonate investment-casting pattern (right) and the steel air inlet housing (right) for a jet turbine engine (Courtesy DTM Corporation)

chosen primarily because the air inlet housing has several overhanging structures from which removal of supports would have been extremely difficult.

Sundstrand designed several iterations of the housing as solid models on its CAD system. These models were converted to the STL format and sent to build the nylon evaluation models. As the program progressed, Sundstrand wanted to test the part. As the designs were finalized, new SLS® versions of the part were created as tooling for investment casting. Polycarbonate patterns were created, sealed with wax and sent for casting. The patterns were first coated with a thin layer of polyurethane to fill any remaining surface pores and provide the necessary surface finish. Then the patterns were used to cast the part in Iconel 718 steel, which were sent back to Sundstrand for testing. In all, Sundstrand saved more than four months of tooling and prototyping time, and saved more than US$88 000.

Fabrication of Flight-Certified Production Castings

Bell Helicopter has successfully used stereolithography, first to verify parts design, then to aid with fit and functional testing, and finally to produce investment casting patterns for the manufacture of Federal Aviation Authority (FAA)-certifiable production parts [25]. About 50 of the parts that made up the new helicopter's flight control system were developed with stereolithography. The largest support structure for the hydraulic system, measured approximately 500 mm × 500 mm × 200 mm, and the smallest, 25 mm × 25 mm × 1.1 mm. In production, all parts will be investment cast, most in aluminum while others will be in steel alloys.

Initially, half-scale models were used for design verification, as they were large enough to confirm design intent and were much quicker to fabricate on the SLA machines. Once a design was finalized, full-size SLA models were fabricated for use in "virtual installation" [25]. In virtual installation, full-sized SLA parts were assembled with other components and installed on the actual production helicopter in order to test the fit and kinematics of the assembly. Parts used for virtual installation included all the features that would normally be machined into rough production castings. Problems associated with interferences and clearances were identified and rectified before they could arise in later stages, which by then would be more costly to rectify.

After virtual installation, Bell made QuickCast™ investment casting patterns of each part. These patterns were sent for casting, with the resulting parts being sent for FAA flight certification. In previous projects, Bell would have machined parts to simulate production castings and send them for certification. When the castings became available in about 45 weeks, the parts would have to be re-certified. With QuickCast™ patterns, Bell could produce production-grade metal investment castings in as little as three weeks and did not need re-certification when wax tooling eventually becomes available. The overall development time was shortened with the use of SLA models and QuickCast™ for creating investment casting came closed to six months, resulting in substantial cost savings and a better product was offered to the market.

AUTOMOTIVE INDUSTRY

Prototyping Complex Gearbox Housing for Design Verification

Volkswagen has utilized Helysis's LOM to speed up the development of a large, complex gearbox housing for its Golf and Passat car lines [26]. The CAD model for the housing was extremely complex and difficult to visualize. VW wanted to build a LOM part to check the design of the CAD model and then use the part for packaging studies.

Using traditional methods, such a prototype would be costly and time consuming to build, and it may not be always possible to include all fine details of the design. Fabrication of the model based on drawings was often subjected to human interpretation, and consequently is error-prone, thus further complicating the prototyping process. All these difficulties were avoided by using RP technology as the fabrication of the model was based entirely on the CAD model created. The gearbox housing was too large for the build volume of the LOM machine. The CAD model was thus split into five sections and re-assembled after fabrication. It took about ten days to make and finish all five sections, and once they were completed, patternmakers glued them together to complete the final model. The LOM model was first used for verifying the design, and subsequently, to develop sand-casting tooling for the creation of metal prototypes. The RP process had shrunk the prototype development time from eight weeks to less than two, and considerable time and cost savings were achieved.

Prototyping Advanced Driver Control System with Stereolithography

At General Motors, in many of its divisions, RP is becoming a necessary tool in the critical race to be first to market [27]. For example, Delco Electronics, its automotive electronics subsidiary, was involved in the development of the Maestro project. Designed to blend an advanced Audio System, a hands-free cellular phone, Global Positioning System (GPS) navigation, Radio Data System (RDS) information, and climate control into a completely integrated driver control system, the Maestro was to be a marvel.

With many uniquely-shaped push-buttons, two active-matrix LCD screens and a local area network allowing for future expansion, the time needed to develop the system was the most critical factor.

Working with Modern Engineering, an engineering service company, Delco Electronics developed the first renderings and concept drawings for the Maestro project. In order to speed up the project, the designers needed the instrument panel with its myriad of push-buttons working early in the design cycle. Unfortunately, the large number of buttons meant a corresponding large number of rubber molds with all the problems associated with the conventional molding process. From the stylist's concepts, models for each button face were manually machined. Once the designs were confirmed, the machined models were laser scanned, generating the CAD data needed for the creation of SLA models. The final prototype buttons needed to be accurate enough to ensure proper fit and function, as well as be translucent, so that they could be back-lit.

The SLA models generated on 3D Systems' SLA machine were accurate enough to be finished, painted and installed in the actual prototype vehicle, eliminating the need for rubber molds. The result was that in less than four months, Delco Electronics was able to complete the functional instrument panel, with all 108 buttons built using the SLA.

Creating Cast Metal Engine Block with RP Process

As new engine design and development is an expensive and time consuming process, the ability to test a new engine and all its auxiliary components before committing to tooling is important in ensuring costs and time savings [28]. The Mercedes-Benz Division of Daimler-Benz AG initiated a program of physical design verification on prototype engines using SLA parts for initial form and fit testing. After initial design reviews, metal components were produced rapidly using the QuickCast™ process.

Their first project was the design and prototyping of a four-cylinder engine block for the new Mercedes-Benz "A-Class" car. The aim was to cast the engine block directly from a stereolithography QuickCast™ pattern. The engine block was designed on Mercedes-Benz own CAD system, and the data were transferred to 3D Systems Technology Center at Darmstadt, where the one-piece pattern of the block was built on the SLA machine. The full scale investment casting pattern was generated in 96 hours.

The pattern was then sent for shell investment casting, resulting in the 300 mm × 330 mm × 457 mm, engine block being cast in A356-T6 aluminum in just five weeks. The completed engine block incorporated the cast-in water jacket, core passage ways, and exhibited Grade B radiographic quality in all areas evaluated. The entire prototyping process using RP technology lasted only six weeks (compared to 15 to 18 weeks using traditional methods), and the approximate cost savings were approximately US$150 000 as compared with traditional methods. These are both significant, especially in the need for a short time-to-market requirement.

Using Stereolithography to Produce Production Tooling

Ford Motor Company has used 3D Systems' QuickCast™ to create the production tool of a rear wiper-motor cover for the 1994 Explorer sport utility vehicle [29, 30]. The part measured approximately 200 mm × 150 mm by 75 mm and was to be injection molded with polypropylene during production. Traditional methods would have provided the necessary tools for molding in three months.

Ford first built the SLA model of the cover and fit it over the wiper motor to verify the design (see Figure 7.11). Dimensional and assembly problems were identified and rectified before the design was confirmed. From the CAD model data, originally created on the CAD software Pro Engineer, the Pro/MOLDDESIGN® software was used to create "negative" mold halves. Shrink factors were then applied to compensate for the photo-curable resin, A2 steel, and polypropylene. The

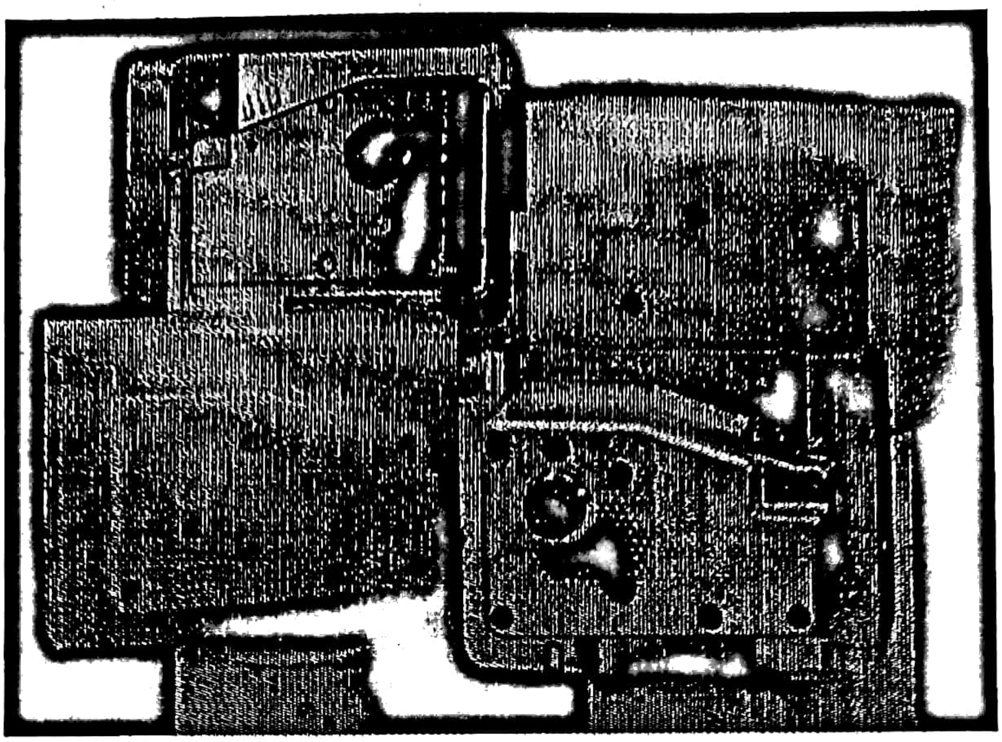

Figure 7.11: QuickCast™ generated patterns and the investment cast inserts for the rear wiper-motor cover

QuickCast™ process was then used to build the SLA patterns of the actual tool inserts (in halves). They were then investment cast out in A2 tool-steel. Once cast, the tool inserts would be fitted onto an injection molding machine and used to produce the plastic wiper-motor covers. With the application of such "rapid tooling" techniques, Ford was able to start durability and water flow testing eighteen months ahead of schedule, with a cost reduction of 45% and time savings of more than 40%.

BIOMEDICAL INDUSTRY

From manufacturing of medical devices and creating customized implants and prostheses to surgical planning and education, RP can be applied to enhance medical applications and healthcare delivery. The following sections relate examples of how RP can play a valuable role in the biomedical industry.

Operation Planning for Cancerous Brain Tumor Surgery

In one case study, a patient had a cancerous bone tumor in his temple area and because of that the surgeon would have to access the growth via the front through the right eye socket. The operation was highly dangerous as damage to the brain was likely which would result in the impairment of some motor functions. In any which way, the patient would have lost the function of the right eye [31]. However, before proceeding with the surgery, the surgeon wanted another examination of the tumor location, but this time using a three-dimensional plastic replica of the patient's skull. By studying the model, the surgeon realized that he could re-route his entry through the patient's jawbone, thus avoiding the risk of harming the eye and motor functions. Eventually, the patient lost only one tooth and of course, the tumor. The plastic RP model used by the surgeon was fabricated by the SLA from a series of 2D CT scans of the patient's skull.

This case study is an excellent example of the potential impact of rapid prototyping in the medical arena. Other case studies relating to bone tumors have also been reported to have had successful results [32, 33]. In all cases, not only was the patient spared physical disability and the emotional and financial price tags associated with that, but the surgeon gain an invaluable insight into his patient through the RP model. The value added to the surgeon's pre-surgical planning stage resulted also in a reduced duration of the procedure and thus the risk of infection and operation costs.

Planning Reconstructive Surgery with RP Technology

Due to a traffic accident, a patient had a serious bone fracture on the upper and lateral orbital rim in the skull [34]. In the first reconstructive surgery, the damaged part of the skull was transplanted with the shoulder bone, but shortly after the surgery, the transplanted bone had dissolved. Thus, it was necessary to perform another surgery to transplant an artificial bone that would not dissolve. The conventional procedure of such a surgery would be for surgeons to manually carve the transplanted bone during the operation until it fitted properly. This operation would have required a lot of time, due to the difficulty in carving bone, let alone during the surgery.

Using rapid prototyping, a SLA prototype of the patient's skull was made and then used to prepare an artificial bone that would fit the hole caused by the dissolution. This preparation not only greatly reduced the time required for the surgery, but also improved its accuracy.

In another case involved at Keio University Hospital of Japan [35], a five-month-old baby had a symptom of scaphocephary in the skull. This is a condition that may lead to serious brain damage because it would only permit the skull to grow in the front and rear directions. The procedure required was to take the upper half of the skull apart and reconstruct it completely, so that the skull would not suppress the brain as the baby grows. Careful planning was essential for the success of such a complex operation. Firstly, the prototype of the skull was produced and amputation lines were drawn on the model. Secondly, a surgical rehearsal was first carried out on the model with the amputation of the skull prototype according to the drawn lines followed by the reconstruction of the amputated part. In this case, the rapid prototype of the skull provided the surgical procedure with: (1) a good three-dimensional visualization support for the planning process, (2) an application as training material, and (3) a guide for the real surgery.

Craniofacial Reconstructive Surgery Planning

Restoration of facial anatomy is required in cases of congenital abnormalities, trauma or post cancer reconstruction. In one case, the patient had a deformed jaw by birth, and a surgical operation was necessary to amputate the shorter side of the jaw and change its position [36]. The difficult part of the operation was the evasion of the nerve canal that runs inside the jawbone. Such an operation was impossible in the conventional procedure because there was no way to visualize the inner nerve canal. Using a CAD model reconstructed from the CT images, it clearly showed the position of the canal and simulation of the amputating process on workstations was a good support for surgeons to determine the actual amputation line.

Figure 7.12: CAD model from laser scanner data of a patient's facial details

Figure 7.13: SLA model of a patient's facial details

Furthermore, the use of a resin prototype of the jawbone allowed the visualization of the internal nerve canal. The semi-transparent prototype facilitated the determination of the amputation line and enabled an efficient surgery simulation with an actual tool.

In another case study, a laser digitizer was used instead of the CT [37] to capture the facial details of a patient with a harelip problem. The triangulated surface of the patient's face was reconstructed in CAD as seen as Figure 7.12. Figure 7.13 shows the SLA prototype derived from the CAD data. In this case study, the prototype model provided the validation for the laser scan measurements. In addition, it facilitated prediction of the surgical outcome and post-operative assessment of changes in facial surgery. Another advantage was that mirror images could be used to reconstruct the CAD model of facial details such as ears to achieve symmetry.

Biopsy Needle Housing

Biomedical applications are extended beyond design and planning purposes. The prototypes can serve as a master for tooling such as a urethane mold. At Baxter Healthcare, a disposable-medical-products company, designers rely on two RP processes: SLA and SGC to create master models from which they develop metal castings [31]. The masters also serve as a basis for multiple sub-tooling processes. For example, after a master model has been generated via one of the RP machines, the engineers might build a urethane mold around it, cut open the mold, pull out the master, then inject thermoset material into the mold to make the prototype parts.

This process is useful in situations where multiple prototypes are necessary because the engineers can either reuse the rubber molds or make many molds using the same master. The prototypes are then delivered to customer focus groups and medical conferences for professional feedback. Design changes are then incorporated into the master CAD database. Once the design is finalized, the master database is used to drive the machining of the part. Using this method, Baxter Healthcare has made models of biopsy needle housing and many other medical products.

Knee Implants

Engineers at DePuy Inc., a supplier of orthopedic implants, have integrated CAD and RP into their design environment, using it to analyze the potential fit of implants in a specific patient and then modifying the implant design appropriately [31]. At DePuy, SLA plays a major role in the production process of all the company's products, standard and custom. The prototypes are also used as masters for casting patterns to launch a product or to do clinical releases of a product.

For this application, there are several advantages over traditional casting tooling. Firstly, the typical ten-week lead-time is reduced. Secondly, the cost of about US$8000 to US$10 000 is reduced too.

Scaffolds for Tissue Engineering

Tissue engineering has been used to replace failing or malfunctioning organs such as skin, liver, pancreas, heart valve leaflet, ligaments, cartilage and bone. This has given rise to the interests in applying RP techniques to build scaffolds either to induce surrounding tissue and cell in-growth or serve as temporary scaffolds for transplanted cells to attach and grow onto. These scaffolds can be designed in three-dimensions on CAD taking into consideration the porosity and good interconnectivity for tissue induction to occur.

The function of cells, such as in bone and cartilage regeneration, is dependent on the three-dimensional spatial relationships. As such, the geometry of these hard tissues are critical to its function [38–41]. RP has been able to lend itself to producing complex geometry scaffolds.

Customized Tracheobronchial Stents

Stents for maintaining the patency of the respiratory channel has been investigated for production using RP techniques [42]. Customization of these stents can be carried out to take into account compressive resistance with respect to stent wall thickness, as well as unique anatomical considerations. Measurements are taken of the actual forces

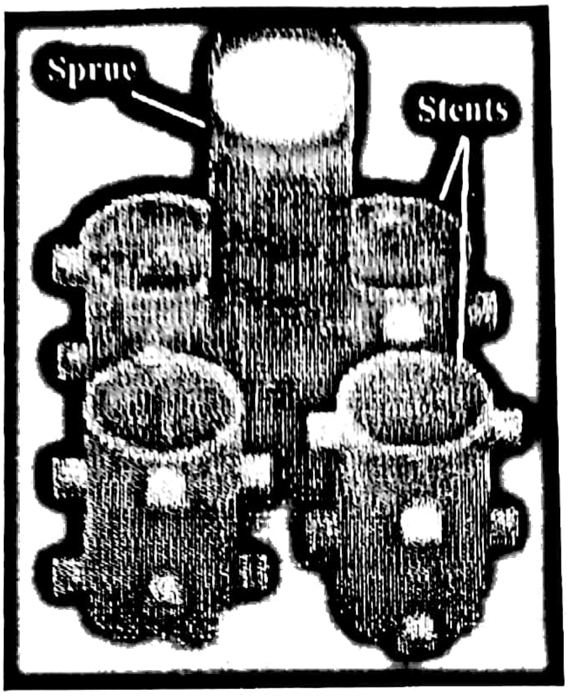

Figure 7.14: Production of the customized stents in slightly differing sizes for an ideal custom fit

required to open the airway channel to its original dimensions. The data is fed to the CAD system where modification on the stent design is carried out. Upon confirmation, the 3D data is fed to an RP system where the master pattern of the model is built. The master pattern then undergoes the silicon molding vacuum casting process, reproducing the stent master pattern with a biocompatible material with all its strength, spring-back and anti-migration properties in place. Figure 7.14 shows four vacuum cast tracheobronchial stents in slightly differing sizes for an ideal intra-surgery custom fit. The stent is sterilized, packaged, and delivered.

Inter-Vertebral Spacers

Human spinal vertebras can disintegrate due to conditions such as osteoporosis or extreme forces acting on the spine. In the management of such situations, a spacer is usually required as part of the spinal fixation process. RP has been investigated for the production of such

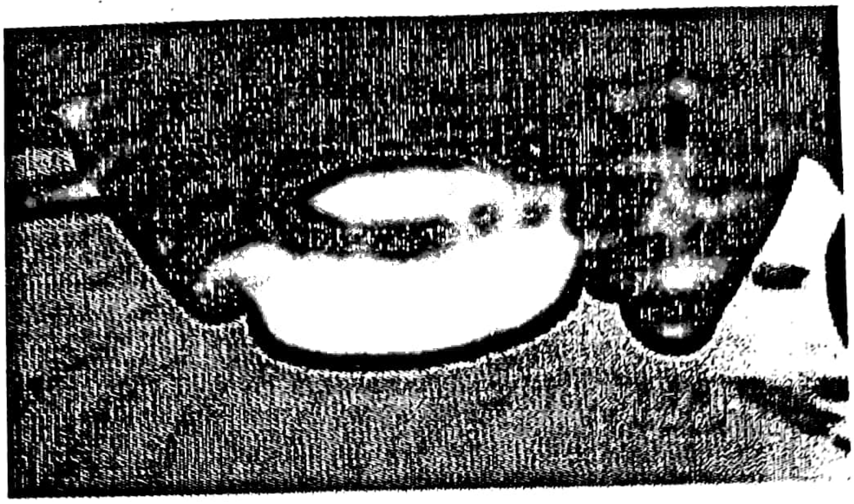

Figure 7.15: Inter-vertebral spacers produced by the RT system at NTU

spacers as it is an ideal process to fabricate 3D structures with good interconnecting pores for the promotion of tissue in-growth. Other considerations for producing such an implant are that the material is biocompatible, and that the mechanical compressive strength of the spacer is able to withstand spinal loads.

A process, developed at the Nanyang Technological University for such a purpose, uses a solid RP master pattern of the spacer to produce a soft mold. Stainless steel bearings coated with a formulated binder system are then cast into the soft mold under vacuum. Upon curing, the part is ejected from the mold. The part then undergoes debinding and sintering processes to produce the final part. The primary advantage of this process is its ability to use a solid RP pattern to produce from this a porous structure with controllable pore sizes and mechanical strengths [43, 44]. Figure 7.15 shows the inter-vertebral spacers using the RT system.

Cranium Implant

A patient suffered from a large frontal cranium defect after complications from a previous meningioma tumor surgery. This left the patient with a missing cranial section, which caused the geometry of the head to look deformed. Conventionally, a titanium-mesh plate would be hand-formed during the operation by the surgeon. This often resulted in inaccuracies and time spent for trial and error. Using RP, standard preparations of the patient were made and a computed tomography (CT) scan of the affected area and surrounding regions was taken during the pre-operation stage. The three-dimensional CT data file was transferred to a CAD system and the missing section of the cranium topography was generated. After some software repair and cleaning up were carried out on the newly generated section, an inverted mold was produced on CAD. This three-dimensional solid model of the mold was saved in *.STL format and transferred to the RP system, such as the SLS®, for building the mold. The SLS® mold was produced and used to mechanically press the titanium-mesh plate to the required three-dimensional profile of the missing cranium section. During the operation, the surgeon cleared the scalp tissue of the defect area and fixated the perfectly pre-profiled plate onto the cranium using self-tapping screws. The scalp tissue was then replaced and sutured. At post-operation recovery, results observed showed improved surgical results, reduced operation time and a reduce probability of complications.

JEWELRY INDUSTRY

The jewelry industry has traditionally been regarded as one which is heavily craft-based, and automation is generally restricted to the use of machines in the various individual stages of jewelry manufacturing. The use of RP technology in jewelry design and manufacture offers a significant breakthrough in this industry. In an experimental computer-aided jewelry design and manufacturing system jointly developed by Nanyang Technological University and Gintic Institute of Manufacturing Technology in Singapore, the SLA (from 3D Systems) was used successfully to create fine jewelry models [45]. These were used as master patterns to create the rubber molds for making wax patterns that were later used in investment casting of the precious metal end product (see Figure 7.16). In an experiment with the design of rings, the overall quality of the SLA models were found to be promising, especially in the generation of intricate details in the design. However, due to the nature of the step-wise building of the model, steps at the "gentler"

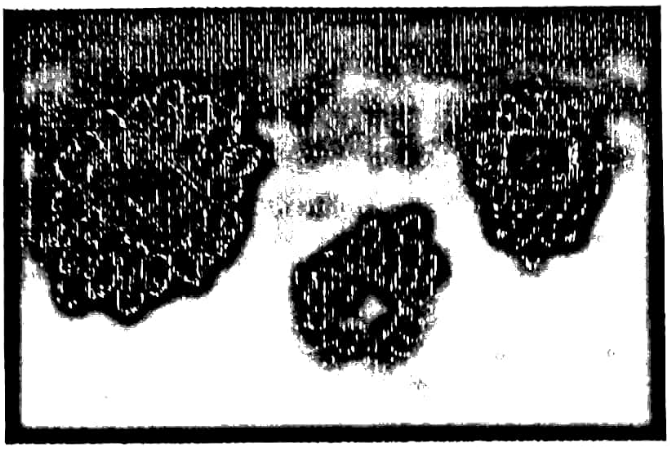

Figure 7.16: An investment cast silver alloy prototype of a broach (right), the full-scale wax pattern produced from the silicon rubber molding (center), and the two-time scaled SLA model to aid visualization (left)

slope of the model were visible. With the use of better resin and finer layer thickness, this problem was reduced but not fully eliminated. Further processing was found to be necessary, and abrasive jet deburring was identified to be most suitable [46].

Though post-processing of SLA models is necessary in the manufacture of jewelry, the ability to create models quickly (a few hours compared to days or even weeks, depending on the complexity of the design) and its suitability for use in the manufacturing process offer great promise in improving design and manufacture in the jewelry industry.

COIN INDUSTRY

Similar to the jewelry industry, the mint industry has traditionally been regarded as very labor-intensive and craft-based. It relies primarily on the skills of trained craftsmen in generating the "embossed" or relief designs on coins and other related products. In another experimental coin manufacturing system using CAD/CAM, CNC and RP technologies developed by Nanyang Technological University and Gintic Institute of Manufacturing Technology in Singapore, the SLA (from 3D Systems) was used successfully with a Relief Creation Software to create tools for coin manufacture [47]. In the system

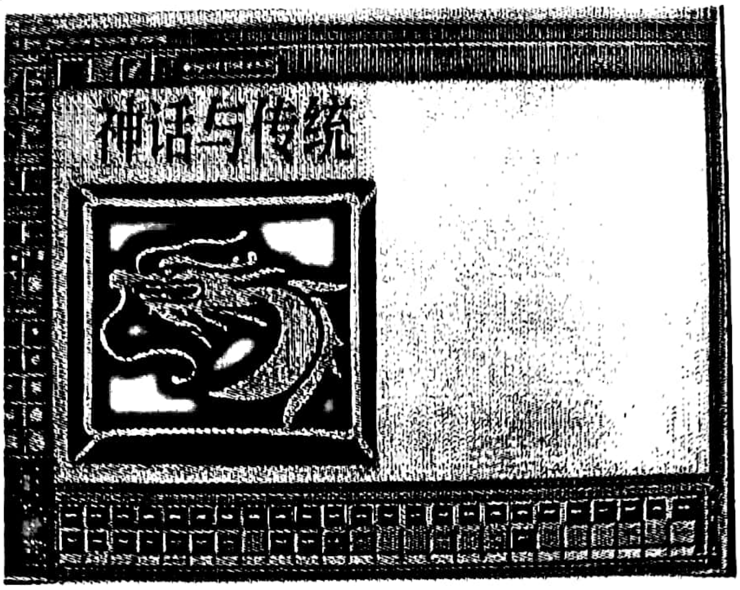

Figure 7.17: Two-dimensional artwork of a series of Chinese characters and a roaring dragon

involving RP technology, its working methodology consists of several steps.

Firstly, 2D artwork is read into ArtCAM, the CAD/CAM system used in the system, utilizing a Sharp JX A4 scanner. Figure 7.17 shows the 2D artwork of a series of Chinese characters and a roaring dragon. In the ArtCAM environment, the scanned image is reduced from a color image to a monochrome image with the fully automatic "Gray Scale" function. Alternatively, the number of colors in the image can be reduced using the "Reduce Color" function. A color palette is provided for color selection and the various areas of the images are colored, either using different sizes and types of brushes or the automatic flood fill function.

The second step is the generation of surfaces. The shape of a coin is generated to the required size in the CAD system for model building. A triangular mesh file is produced automatically from the 3D model. This is used as a base onto which the relief data is wrapped and later combined with the relief model to form the finished part.

The third step is the generation of the relief. In creating the 3D relief, each color in the image is assigned a shape profile. There are various fields that control the shape profile of the selected colored

Figure 7.18: Three-dimensional relief of artwork of the roaring dragon

region, namely, the overall general shape for the region, the curvatures of the profile (convex or concave), the maximum height, base height, angle and scale. The relief detail generated can be examined in a dynamic Graphic Window within the ArtCAM environment itself. Figure 7.18 illustrates the 3D relief of the roaring dragon artwork.

The fourth step is the wrapping of the 3D relief onto the coin surface. This is done by wrapping the three-dimensional relief onto the triangular mesh file generated from the coin surfaces. This is a true surface wrap and not a simple projection. The wrapped relief is also converted into triangular mesh files. The triangular mesh files can be used to produce a 3D model suitable for color shading and machining. The two sets of triangular mesh files, of the relief and the coin shape, are automatically combined. The resultant model file can be color-shaded and used by the SLA to build the prototype.

The fifth step is to convert the triangular mesh files into the STL file format. This is to be used for building the RP model. After the conversion, the STL file is sent to the SLA to create the 3D coin pattern which will be used for proofing of design [47].

TABLEWARE INDUSTRY

In another application to a traditional industry, the tableware industry, CAD and RP technologies are used in a integrated system to create better designs in a faster and more accurate manner. The general methodology used is similar to that used in the jewelry and coin industries. Additional computer tools with special programs developed to adapt decorative patterns to different variations of size and shape of tableware are needed for this particular industry [48]. Also a method for generating motifs along a circular arc is also developed to supplement the capability of such a system [49].

The general steps involved in the art to part process for the tableware include the following:

(1) Scanning of the 2D artwork.
(2) Generation of surfaces.
(3) Generation of 3D decoration reliefs.
(4) Wrapping of reliefs on surfaces.
(5) Converting triangular mesh files to STL file.
(6) Building of model by the RP system.

Two RP systems are selected for experimentation in the tableware system. One is 3D Systems' SLA, and the other is Helysis' LOM. The SLA has the advantages of being a pioneer and a proven technology with many excellent case studies available. It is also advantageous to use in tableware design as the material is translucent thus allowing designers to view the internal structure and details of tableware items like tea pots and gravy bowls. On the other hand, the use of LOM has its own distinct advantages. Its material cost is much lower and because it does not need support in its process (unlike the SLA), it saves a lot of time in both pre-processing (deciding where and what supports to use) and post-processing (removing the supports). Examples of dinner plates built using the systems are shown in Figure 7.19.

In an evaluation test of making the dinner plate prototype, it was found that the LOM prototype is able to recreate the floral details more accurately. The dimensional accuracy is slightly better in the LOM prototype. In terms of the build-time, including pre- and post-processing, the SLA is about 20% faster than the LOM process. However, with sanding and varnishing, the LOM prototype is found to be a better model which can be used later to create the plaster of Paris molds for the molding of the ceramic tableware (see Figure 7.20 for a tea-pot built using LOM). Apart from these technical issues, the

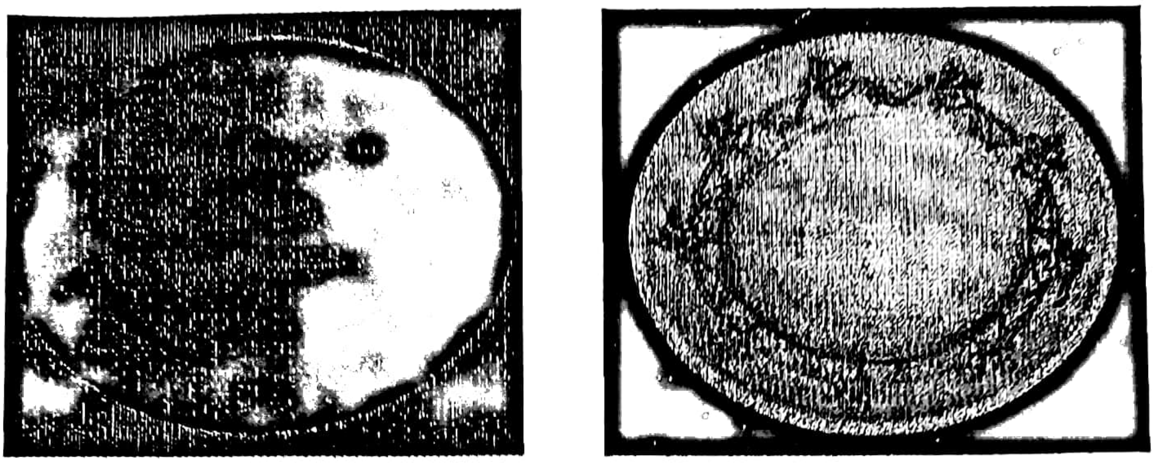

Figure 7.19: Dinner plate prototype built using SLA (left) and LOM (right)

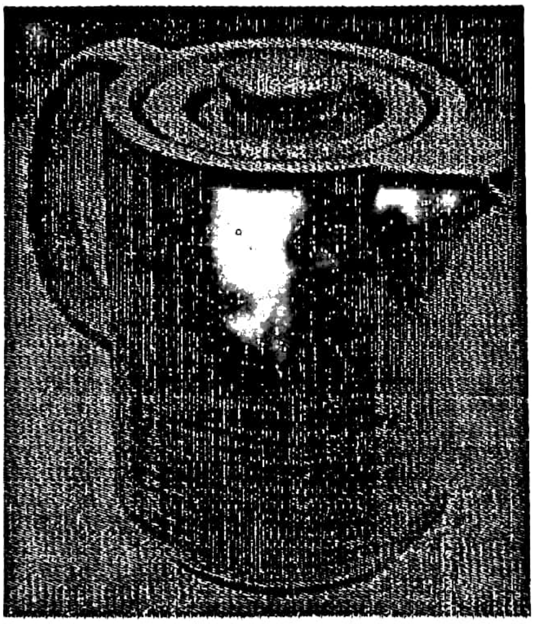

Figure 7.20: LOM model of a tea pot (Courtesy of Champion Machine Tools, Singapore)

initial investment, operating and maintenance costs of the SLA are considerably higher than that of the LOM, estimated to be about 50% to 100% more.

In the ceramic tableware production process, the LOM model can be used directly as a master pattern to produce the block mold. The mold is made of plaster of Paris. The result of this trial is shown in Figure

The trials highlighted the fact that plaster of Paris is an extremely good material for detailed reproduction. Even slight imperfections, left

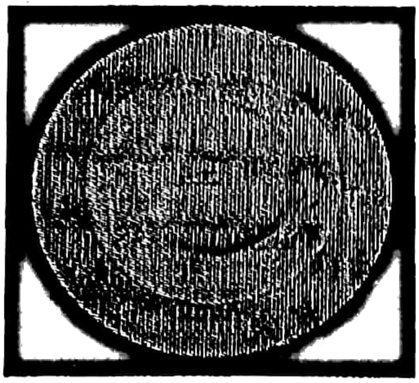

Figure 7.21: Block mold cast from the LOM model of the dinner plate (Courtesy of Oriental Ceramics Sdn. Bhd., Malaysia)

after hand finishing the LOM model, are faithfully reproduced in the block mold and pieces cast from these molds.

Whichever RP technology is adopted, such a system saves time in designing and developing tableware, particularly in building a physical prototype. It can also improve designs by simply amending the CAD model and the overall system is easy and friendly to use.