Rapid prototyping and rapid tooling—the key enablers for rapid manufacturing

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Abstract: Rapid manufacturing is a new mode of operation that can greatly improve the competitive position of companies adopting it. The key enabling technologies of rapid manufacturing are rapid prototyping (RP) and rapid tooling (RT). This paper classifies the existing RP processes and briefly describes those with actual or potential commercial impact. The paper then discusses five important RP applications: building functional prototypes, producing casting patterns, making medical and surgical models, creating artworks and fabricating models to assist engineering analysis. Finally, the paper gives an overview of indirect and direct RT methods for quickly producing up to several thousand parts together with examples illustrating different applications of RT.

Keywords: rapid prototyping, rapid tooling, rapid manufacturing

1 INTRODUCTION

Global competition, mass customization, accelerated product obsolescence and continued demands for cost savings are forcing companies to look for new ways to improve their business processes. Rapid prototyping (RP) and rapid tooling (RT) have emerged as key enablers for rapid manufacturing, a new mode of operation promising improvements to the competitive position of companies adopting it.

RP is a technology for quickly fabricating physical models, functional prototypes and small batches of parts directly from computer aided design (CAD) data. RT generally concerns the production of moulds and tooling inserts using RP. RP and RT are means for compressing the time-to-market of products and, as such, are competitiveness-enhancing technologies.

This paper starts with a classification of existing RP processes and a brief description of those currently with a significant commercial impact or expected to be in such a position in the near future. Five different application areas of RP are discussed, in particular: building functional prototypes, patterns for castings, medical and surgical models, artworks and models for engineering analysis. The paper then reviews indirect and direct RT methods that are, or shortly will be, available for production runs of up to several thousand parts in a material identical or very similar to that of the final production part. Three examples illustrating different applications of RT conclude the paper.

2 RAPID PROTOTYPING

RP processes may be divided broadly into those involving the addition or the removal of material. According to Kruth [**1**], material accretion processes may be categorized by the state of the prototype material before part formation, namely liquid, powder or solid sheets. Liquid-based processes may entail the solidification of a resin on contact with a laser, the solidification of an electrosetting fluid or the melting and subsequent solidification of the prototype material. Processes using powders (discrete particles) aggregate them either with a laser or by the selective application of binding agents. Those processes that employ solid sheets may be classified into two types depending on whether the sheets are bonded with light or with an adhesive.

Material accretion processes may also be clustered according to the mechanism employed for transferring data from the sliced three-dimensional models into physical structures. Following this method of categorization, the processes fall into one of four groups:

1. *One-dimensional channel.* The first group of processes transfers data using one-dimensional channels. These

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data channels may be realized in the form of a laser beam, an extrusion head, a jet of thermoplastic, a nozzle spraying a binder, a welding head, a cutter or a computerized knife.

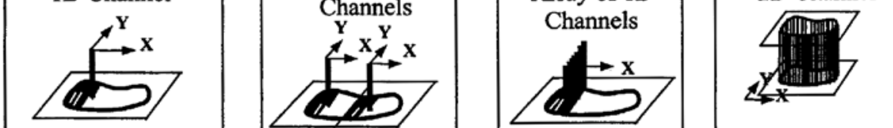
2. *Multiple one-dimensional channels.* A process in this category would employ multiple one-dimensional channels working in parallel. Currently, there is only one process implementing this data transfer method with two independently controlled lasers. However, this multichannel approach could be adopted for other processes in the first group to multiply productivity without introducing any changes to the fundamental working principles.
3. *Array of one-dimensional channels.* The third group includes processes that utilize arrays of one-dimensional channels to construct three-dimensional structures. These may be arrays of nozzles or jets. Currently, RP systems with the highest build speeds all use this mechanism for data transfer.
4. *Two-dimensional channel.* The fourth group includes processes employing two-dimensional channels, e.g. masks. At present, there are only a few processes using this mechanism although it offers significant productivity advantages over the other three approaches.

Figure 1 shows a classification of RP processes that takes into account both the state of materials before part formation and the mechanism employed for data transfer. In the following section, material accretion processes are presented according to the build material used.

2.1 Material accretion processes

2.1.1 Liquid polymer

Of the six processes in this category, which all involve the solidification of a resin by applying electromagnetic radiation, two construct the part using points to build up the layers while the other four solidify entire layers or surfaces at once:



	1D Channel	Multiple 1D Channels	Array of 1D Channels	2D Channel
Liquid Polymer	SL, LTP		Objet	SGC, RMPD, HIS
Discrete Particles	SLS, LST, LENS, LCVD, SLRS, GPD, SALD	LST	3DP	DPS
Molten Material	FDM, BPM, 3DW, PDM		MJM	SDM
Solid Sheets	LOM, PLT			SFP
Electroset Fluids				ES

Ballistic Particle Manufacture (BPM)
Direct Photo Shaping (DPS)
Electrosetting (ES)
Fused Deposition Modelling (FDM)
Gas Phase Deposition (GPD)
Holographic Interference Solidification (HIS)
Laminated Object Manufacturing (LOM)
Laser-Assisted Chemical Vapor Deposition (LCVD)
Laser Engineering Net Shaping (LENS™)
Laser-Sintering Technology (LST)
Liquid Thermal Polymerisation (LTP)
Multi Jet Modelling (MJM)
Objet Quadra Process (Objet)
Paper Lamination Technology (PLT)
Precision Droplet-Based Net-Form Manuf. (PDM)
Rapid Micro Product Development (RMPD)
Shape Deposition Manufacturing (SDM)
Selective Area Laser Deposition (SALD)
Selective Laser Reactive Sintering (SLRS)
Selective Laser Sintering (SLS)
Solid Foil Polymerisation (SFP)
Solid Ground Curing (SGC)
Stereolithography (SL)
Three-Dimensional Printing (3DP)
Three-Dimensional Welding (3DW)

Fig. 1 Classification of rapid prototyping processes

1. *Stereolithography (SL)*. This process relies on a photosensitive liquid resin which forms a solid polymer when exposed to ultraviolet (UV) light. SL systems consist of a build platform (substrate) which is mounted in a vat of resin and a UV helium–cadmium or argon ion laser [**2**]. The first layer of the part is imaged on the resin surface by the laser using information obtained from the three-dimensional solid CAD model. Once the contour of the layer has been scanned and the interior hatched, the platform is lowered and a new layer of resin is applied. The next layer may then be scanned. Once the part is completed, it is removed from the vat and the excess resin drained. The 'green' part is then placed in a UV oven to be post-cured. To broaden the application area of SL, research and technology development efforts have been directed towards process optimization [**3, 4**].
2. *Liquid thermal polymerization (LTP)*. This process is similar to SL except that the resin is thermosetting and an infrared laser is used to create voxels (three-dimensional pixels). This means that the size of the voxels may be affected through heat dissipation, which can also cause unwanted distortion and shrinkage in the part [**1**]. The system is still being researched.
3. *Holographic interference solidification (HIS)*. A holographic image is projected into the resin, causing an entire surface to solidify. Data are still obtained from the CAD model, although not as slices [**1**]. There are no commercial systems available yet.
4. *Solid ground curing (SGC)*. This system again utilizes photopolymerizing resins and UV light [**5**]. Data from the CAD model are used to produce electrostatically a mask on a glass that is developed using a toner. Then the mask is placed above the resin surface and the entire layer is illuminated with a powerful UV lamp. Once the layer has been cured, the excess resin is wiped away and any spaces are filled with wax. The wax is cooled with a chill plate, milled flat and the wax chips removed. A new layer of resin is applied and the process is repeated.
5. *Rapid micro product development (RMPD)*. The RMPD process is a mask-based technology very similar to that of photolithography as used in microelectronics manufacture [**6**]. CAD data are employed to produce masks for laser polymerization of a liquid photoresin in a layer-by-layer fashion. The process allows micro components to be built with a minimum layer thickness of 1 μm and X–Y resolution of 10 μm. In addition, this process can be used to create complex micro systems that integrate electronics, optical and mechanical components.
6. *Objet Quadra process.* The process employs 1536 nozzles to build parts by spreading layers of photosensitive resin that are then cured, layer by layer, using two UV lights. The intensity of the lights and the exposure are controlled so that models produced by the system do not require post-curing. To support overhanging areas and undercuts, Objet deposits a second material that can be separated easily from the model [**7**].

2.1.2 Molten material

There are six processes that involve the melting and subsequent solidification of the part material. Of these, the first five deposit the material at discrete points while the sixth manufactures whole layers at once:

1. *Ballistic particle manufacture (BPM)*. The process builds parts by ejecting a stream of molten material from a nozzle. The stream separates into droplets that hit the substrate and immediately cold-weld to form the part [**8**]. Commercial systems based on this process were available until 1998.
2. *Multi jet modelling (MJM)*. The process builds models using a technique similar to inkjet or phase-change printing but applied in three dimensions [**9**]. A 'print' head comprising 352 jets forming a linear array builds models in successive layers, each individual jet depositing a specially developed thermopolymer material only where necessary (Fig. 2). The MJM head shuttles back and forth along the X axis like a line printer. If the part is wider than the MJM head, the platform repositions itself (Y axis) to continue building the layer. When a layer is completed, the platform is moved away from the head (Z axis) which begins to create the next layer. At the end of the build, support structures are brushed off to finish the model.
3. *Fused deposition modelling (FDM)*. FDM systems consist of two movable heads (one for building the part and one for the supports) which deposit threads of molten material onto a substrate. The material is heated just above its melting point so that it solidifies

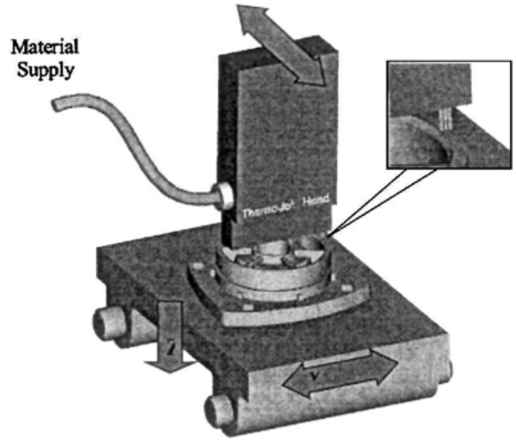


Fig. 2 Multi jet modelling head

immediately after extrusion and cold-welds to the previous layers [**10**].

4. *Three-dimensional welding (3DW)*. This experimental system uses an arc-welding robot to deposit material on a platform as simple shapes which may then be built into more complex structures [**11**]. Unlike most RP processes, the prototypes are built using computer numerically controlled (CNC) programs generated directly from the CAD files instead of employing slice data. Another experimental system deposits the weld material in layers. Feedback control is established by means of thermocouples which monitor the temperature and operate an on-line water cooling system. A grit-blasting nozzle minimizes the oxidization of the part and a suction pump and vacuum nozzle remove excess water vapour and grit [**12**].
5. *Precision droplet-based net-form manufacturing (PDM)*. This is a droplet-based net-forming manufacturing technique [**13**]. The process exploits the capillary instability phenomenon of liquid jets for producing uniform liquid metal droplets. The thermal state and mass flux of the droplets can be controlled to tailor the microstructure of the deposit. There is no commercial system based on this process.
6. *Shape deposition manufacturing (SDM)*. Still experimental, this layer-by-layer process involves spraying molten metal in a near-net shape on to a substrate and then removing unwanted material via numerically controlled (NC) operations [**14**]. Support material is added in the same way either before or after the prototype material, depending on whether the layer contains undercut features (Fig. 3). The added material bolsters subsequent layers. If the layer is complex, support material may need to be added both before and after the prototype material. Each layer is then shot-peened to remove residual stresses. The prototype is transferred from station to station using a robotized pallet system. To date, stainless steel parts supported with copper have been produced. The copper may then be removed by immersion in nitric acid. These prototypes have the same structure as cast or welded parts and the accuracy of NC milled components.

2.1.3 Processes involving discrete particles

These processes build the part by joining powder grains together using either a laser or a separate binding material. The main processes in this category are described briefly below:

1. *Selective laser sintering (SLS)*. SLS uses a fine powder which is heated with a CO_2 laser so that the surface tension of the particles is overcome and they fuse together. Before the powder is sintered, the entire bed is heated to just below the melting point of the material in order to minimize thermal distortion and facilitate fusion to the previous layer [**15**]. The laser is modulated such that only those grains that are in direct contact with the beam are affected. A layer is drawn on the powder bed using the laser to sinter the material. The bed is then lowered and the powder-feed cartridge raised so that a covering of powder can be spread evenly over the build area by a counter-rotating roller. The sintered material forms the part while the unsintered powder remains in place to support the structure and may be cleaned away and recycled once the build is complete (Fig. 4). There is another process, *laser sintering technology*

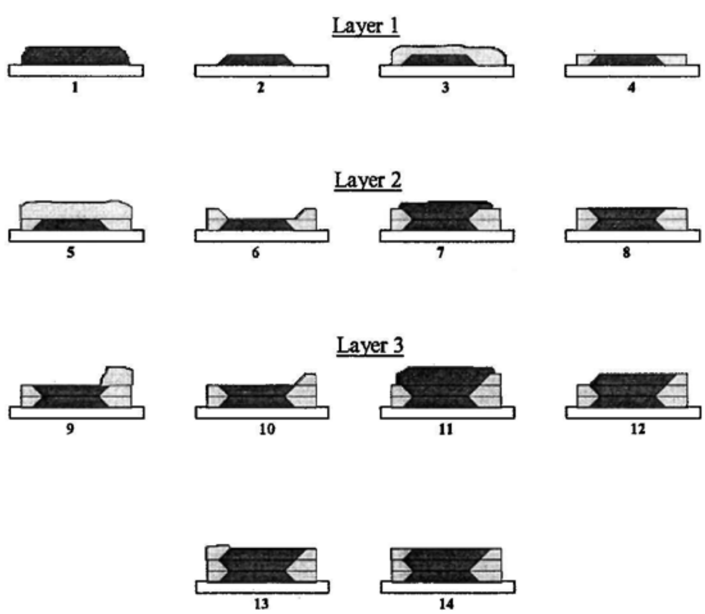


Fig. 3 Shape deposition manufacturing. The construction of the first three layers of a part is shown [**14**]

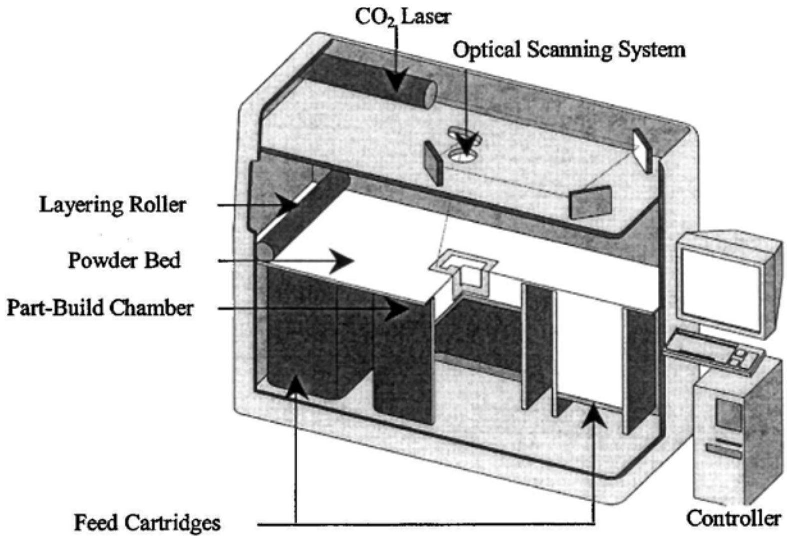


Fig. 4 Selective laser sintering

(LST), that employs the same physical principles. Figure 5 shows an LST system equipped with two laser beams working in parallel. Currently such dual-laser systems are available for processing thermoplastics and sand. Significant development efforts have been directed towards process optimization [**2, 15–18**] to widen the range of applications of SLS and LST.

2. *Laser engineering net shaping (LENS™)*. The LENS process involves feeding powder through a nozzle on to the part bed while simultaneously fusing it with a laser (Fig. 6) [**19**]. The powder nozzle may be on one side of the bed or coaxial with the laser beam. If it is to a side, a constant orientation to the part creation direction must be maintained to prevent solidified sections from shadowing areas to be built. When the powder feeder is coaxial, there may be inaccuracies in the geometry of the part and the layer thickness if the beam and the powder feeder move out of alignment. Because the stream of powder is heated by the laser, fusion to the previous layer is facilitated. Other systems have also been developed based on the same principle, in particular *direct metal deposition (DMD)* [**20**] and *AeroMet laser additive manufacturing* [**21**].

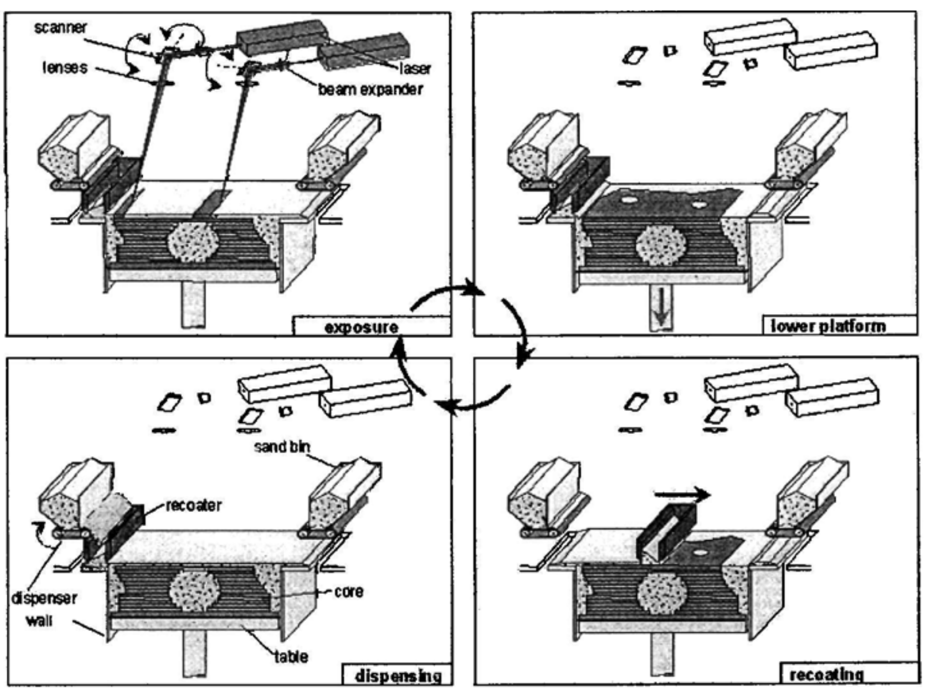


Fig. 5 A dual laser LST system. (Courtesy of EOS GmbH)

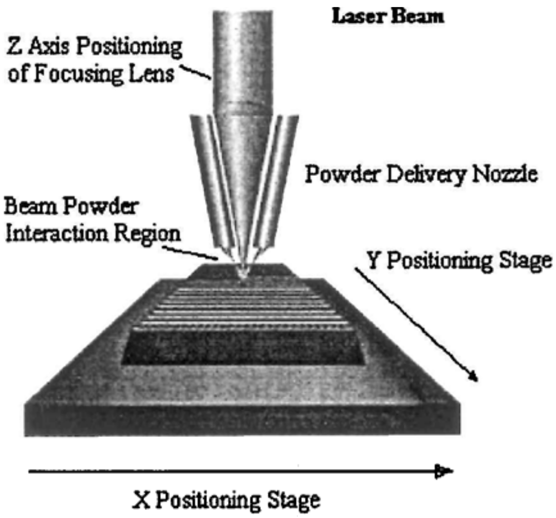


Fig. 6 LENS™ process. (Courtesy of Optomec Design Company)

3. *Gas phase deposition (GPD)*. In this process, the molecules of a reactive gas are decomposed using a laser to generate a solid [**2**]. The resulting solid then adheres to the substrate to form the part. Three slightly different methods of constructing the part have been investigated. With the first method, *selective area laser deposition (SALD)*, the solid component of the decomposed gas is all that is used to form the part. It is possible to construct parts made from carbon, silicon, carbides and silicon nitrides in this way. The second method, *laser-assisted chemical vapour deposition (LCVD)*, spreads a thin covering of powder for each layer and the decomposed solids fill in the spaces between the grains. With the third method, *selective laser reactive sintering (SLRS)*, the laser initiates a reaction between the gas and the layer of powder to form a solid part of silicon carbide or silicon nitride. There are no commercial GPD systems available yet.
4. *Direct photo shaping (DPS)*. The process employs a digital micromirror device (DMD™) array [**22**] as a mask to photocure selectively layer-by-layer polymerizable compositions. The DMD array integrates more than 500 000 microscopic mirrors that can be electronically tilted to reflect visible light on to the photocurable slurry [**23**]. No commercial DPS systems are available yet.
5. *Three-dimensional printing (3DP)*. The process builds parts by first applying layers of powder to a substrate and then selectively joining the particles using a binder sprayed through a nozzle [**24**]. Once the build is completed, the excess powder, which was supporting the model, is removed, leaving the fabricated part. Since there is no state change involved in this process, distortion is reduced [**25**].

2.1.4 Solid sheets

There are three different processes that employ foils to form the part, namely:

1. *Laminated object manufacturing (LOM)*. The build material is applied to the part from a roll and is then bonded to the previous layers using a hot roller which activates a heat-sensitive adhesive [**26**]. The contour of each layer is cut with a CO_2 laser that is carefully modulated to penetrate to the exact depth of one layer. Unwanted material is trimmed into rectangles to facilitate its later removal, but remains in place during the build to act as supports. Separating LOM models from the surrounding excess material can still be a lengthy and tedious task. A method that speeds up and simplifies it has recently been developed [**27**].
2. *Paper lamination technology (PLT)*. The PLT process is very similar to LOM. The main differences between the LOM and PLT processes are in the material used and the methods employed for cutting the contours of the part cross-sections, which in the case of the PLT process is a computerized knife. The PLT process prints the cross-section of the part on to a sheet of paper, which is then applied to the work-in-progress and bonded using a hot roller [**28**].
3. *Solid foil polymerization (SFP)*. The part is built up using semi-polymerized foils which are soluble in monomer resin. On exposure to UV light, the foil solidifies and bonds to the previous layer. It also becomes insoluble. Once the cross-section has been illuminated, a new foil can be applied. The areas of foil that do not constitute the eventual part are used to support it during the build process, but remain soluble and so are easy to remove [**1**, **29**]. No commercial systems are available yet.

2.1.5 Electroset fluid: electrosetting (ES)

Electrodes are printed on to a conductive material such as aluminium. Once all the layers have been printed, they are stacked, immersed in a bath of electrosetting fluid and energized. The fluid that is between the electrodes then solidifies to form the part. Once the composite has been removed and drained, the unwanted aluminium may be trimmed from the part.

Advantages of this technology are that the part density, compressibility, hardness and adhesion may be controlled by adjusting the voltage and current applied to the aluminium. Parts may be made from silicon rubber, polyester, polyurethane or epoxy. The hardware for such a system may be inexpensively bought off the shelf [**12**].

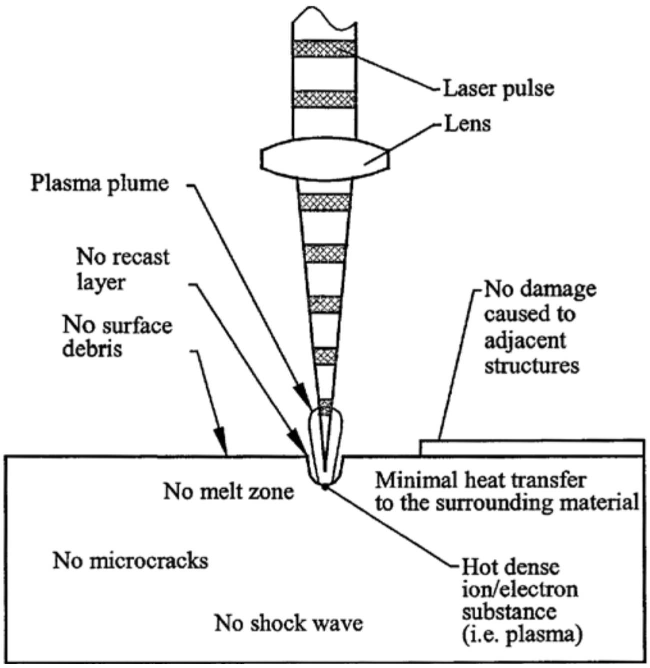


Fig. 7 Femto- and picosecond laser ablation

2.2 Material removal processes

This category includes two processes, *desktop milling (DM)* and *laser milling (LM)*. DM is a process that removes material from the workpiece, as in traditional machining, instead of creating the part by gradual material build-up [**30**]. Prototypes can be made with a high degree of accuracy because they do not deform after they have been completed.

LM is a new process for fabricating relatively small prototype components in advanced engineering materials such as ceramics, titanium and nickel alloys. This process removes material as a result of interaction between a laser beam and a workpiece. Several mechanisms exist for material removal, depending on the laser pulse duration and some material-specific time parameters [**31–33**]. The laser ablation mechanisms for femtosecond and picosecond pulses are alike and can be regarded as a direct solid–vapour transition (sublimation), with negligible thermal conduction into the substrate and almost no heat-affected zone (Fig. 7) [**33–37**]. For nanosecond and longer pulses, the absorbed energy from the laser pulse melts the material and heats it to the vaporization temperature (Fig. 8). There is enough time for a thermal wave to propagate into the material. Evaporation occurs from the liquid material. The molten material is partially ejected from the cavity by the vapour and plasma pressure, but a part of it remains near the surface, held by surface tension forces. After the end of a pulse, the heat quickly dissipates into the bulk of the material and a recast layer is formed.

A number of techniques for LM have been developed. They differ from one another in the applied laser source, the relative beam-workpiece movements and the laser spot characteristics. A common feature of all LM techniques is that the final part geometry is created in a layer-by-layer fashion by generating overlapping craters. Within an individual layer, these simple volumes are arranged in such a manner that each slice has a uniform thickness. Through relative movements of the laser beam and the workpiece, the microcraters produced by individual laser pulses sequentially cover complete layers of the part. The LM process is flexible and can be employed in a wide range of applications, from one-off part production to the manufacture of small batches [**38–40**].

3 APPLICATIONS OF RAPID PROTOTYPING TECHNOLOGY

RP models are becoming widely used in many industrial sectors. Initially conceived for design approval and part verification, RP now meets the needs of a wide range of applications from building test prototypes with material properties close to those of production parts to fabricating models for art and medical or surgical uses. In order to satisfy the specific requirements of a growing number of new applications, special software tools, build techniques and materials have been developed. Five examples in different application areas are described in this section.

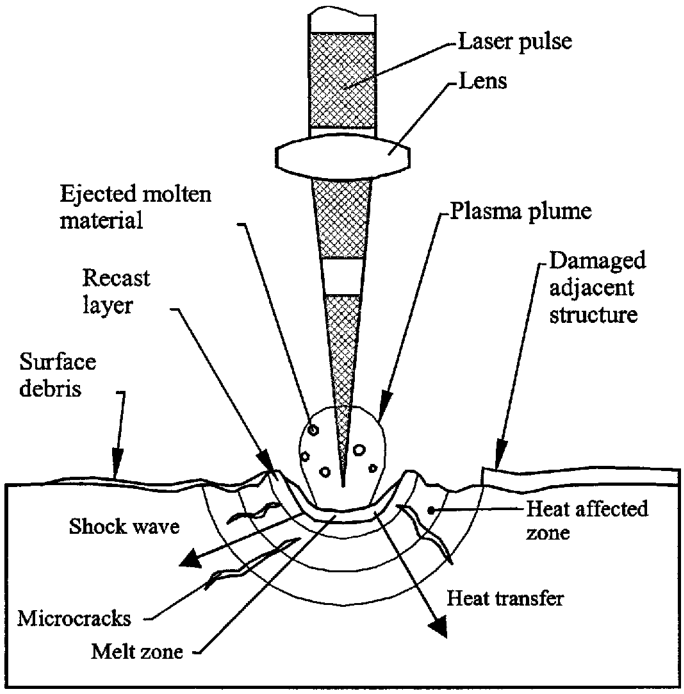


Fig. 8 Nanosecond and longer pulse laser ablation

3.1 Functional models

One of the RP processes that is widely used for producing polyamide-based models for functional tests is SLS. The SLS production of polyamide parts is generally cost effective when a small number (1–5) of parts is required.

The housing in Fig. 9 is a test part built in glass-filled polyamide (a blend of 50 per cent by weight of polyamide powder with a mean particle size of 50 μm and 50 per cent by weight of spherical glass beads with an average diameter of 35 μm) because it is required to withstand harsh test conditions including temperatures of about 100 °C. As a base part for mounting precision components, it has to keep its dimensions within close limits.

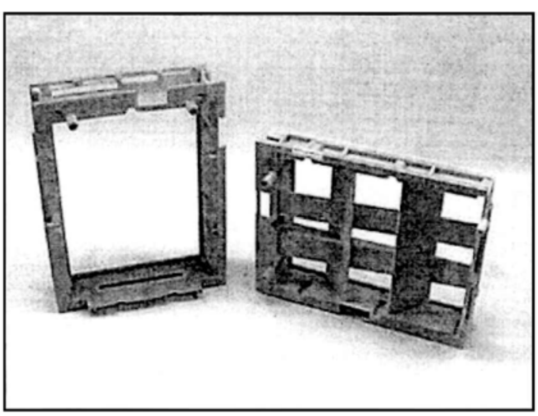
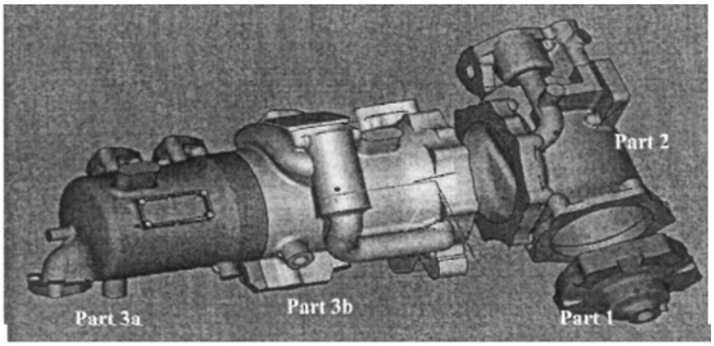


Fig. 9 Composite nylon housing: without ribs (left) and with ribs (right)

Due to its overall dimensions ($190 \times 50 \times 250$ mm), the part was constructed vertically to fit within the build area ($\oslash 305 \times 410$ mm) of the SLS machine used (DTM Sinterstation 2000). The first part manufactured suffered from much distortion; there was vertical growth and 'wash out' (loss of definition and rounding of edges) on the downward facing surfaces and the external dimensions of the sidewalls varied by more than 1 mm. This problem was solved by making the wall thickness uniform and reducing it to 2 mm. Furthermore, 2 mm non-functional ribs were added across the housing to stiffen it. Two ribs were positioned vertically and two others horizontally, as shown in Fig. 9. The number and size of the ribs were determined empirically to constrain post-process distortion in the X and Y directions without adding too much build time. The ribs were also located so that they could easily be removed by machining after completing the build. Subsequently, manufactured parts had much better dimensional accuracy. The errors in 90 per cent of all functional dimensions for the modified part were between $+0.35$ and -0.31 mm.

3.2 Patterns for investment and vacuum casting

RP technologies are widely used for building patterns for investment and vacuum casting. For example, models built in SLA, SLS and FDM can be employed as patterns for both casting processes. The example discussed below illustrates the use of the SLS process to build investment casting patterns in CastForm [**41, 42**].



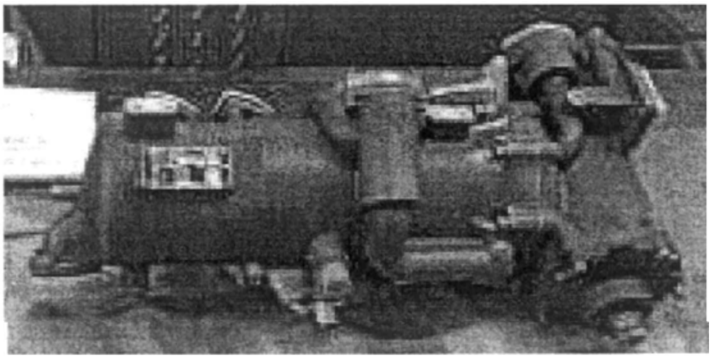


Fig. 10 Heat exchanger for a Pratt and Whitney PW6000 engine

CastForm is a polystyrene-based powder that gives a low ash content and is compatible with standard foundry practices. Processing CastForm creates porous low-density parts that have to be subsequently infiltrated with a low-ash foundry wax to yield patterns containing 45 per cent polystyrene and 55 per cent wax.

The heat exchanger assembly of a Pratt and Whitney PW6000 engine shown in Fig. 10 was produced using CastForm patterns. The assembly includes three cast aluminium components that have to withstand high temperature and pressure. These complex castings are essentially pressure vessels with multiple portings, mountings and sensor pads. The largest component measures 600 mm in height and 325 mm in diameter (Fig. 10). Several sets of sacrificial casting patterns were built using the SLS process. The errors in 90 per cent of all functional dimensions were between $+0.25$ and -0.25 mm. The accuracy of the patterns was highly dependent on their size, the largest errors being found on the largest dimensions. However, although some dimensions were out of the required general tolerances (± 0.125 mm), the aluminium castings were fully satisfactory as any deviations were corrected when some of the features were machine-finished afterwards.

The main benefit of employing the SLS process was that the design team was able to incorporate major and minor modifications into the CAD models between the builds. There was no need to freeze the design before proceeding to manufacture. The prototype heat exchangers underwent stringent testing before the design was approved. As a relatively small number of exchangers was required per year, the SLS process was approved as a production method for the fabrication of the required casting patterns. In general, RP patterns are a cost effective alternative when a small number of parts, say up to 50, of complex design are required and the cost of a mould tool for wax patterns is prohibitive.

3.3 Medical or surgical models

RP technologies are applied in the medical/surgical domain for building models that provide visual and tactile information. In particular, RP models can be employed in the following applications [**43–47**]:

1. *Operation planning.* Using real-size RP models of patients' pathological areas, surgeons can more easily understand physical problems and gain a better insight into the operations to be performed. RP models can also assist surgeons in communicating the proposed surgical procedures to patients.
2. *Surgery rehearsal.* RP models offer unique opportunities for surgeons and surgical teams to rehearse complex operations using the same techniques and tools as in actual surgery. Potentially, such rehearsals can lead to changes in surgical procedures and significantly reduce risks.
3. *Training.* RP models of specimens of unusual medical deformities can be built to facilitate the training of

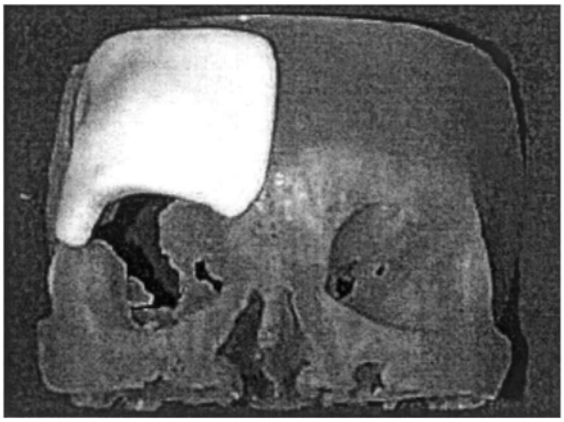


Fig. 11 The SLA model with the resection template [**45**]

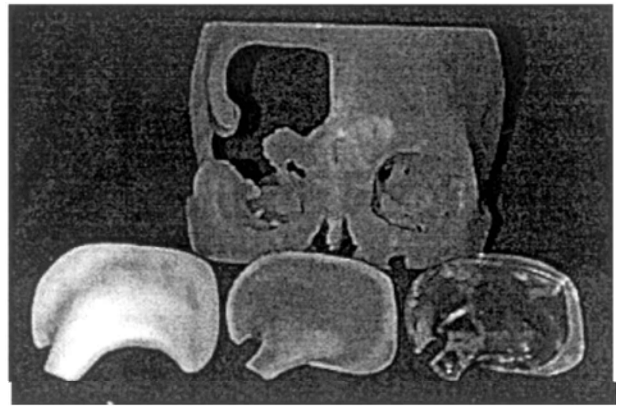


Fig. 12 The SLA model together with the template and the implant [**45**]

student surgeons and radiologists. Such models can also be employed for student examinations.

4. *Prosthesis design.* RP models can be used to fabricate master patterns which are then replicated using a biocompatible plastic material. Implants produced in this way are much more accurate and cost effective than those created conventionally.

The following example, reported by a company in Queensland, Australia, demonstrates the use of RP models in the medical domain. Two SLA medical models were built for a patient suffering from a secondary carcinoma of the right superior orbital margin and the adjacent frontal bone. The first model was used to plan the resection of the cancerous bone and also as an operation reference and patient consent tool. The SLA model can be cut with the same surgical tools as those used for bone resectioning. A resectioned template was created in plastic following the surgeon's desired resection line. The fabricated plastic template was placed over the model to check the match with the surgeon's resection line (Fig. 11). The second model was then employed to construct an acrylic custom implant (Fig. 12). The unaffected left superior orbital margin was mirrored across to assist the design of the implant. The resection template and the custom implant were prepared for the operation by gas sterilization. The template was then placed on to the lesion and the resection line traced out and the bone cut away. Finally, the implant was inserted into the space vacated by the removed bone. The operation was reported as a complete success and the surgeon was fully satisfied with the quality and the cost of utilizing RP models.

3.4 Art models

Another growing application area for RP technologies is art and design. Through building RP models, artists can experiment with complex artworks that support and enhance their creativity. Initially, the high cost of RP models meant strict limits on the size of the models. However, recently, with the introduction of concept modellers, which are relatively inexpensive RP machines for quickly producing design models, it has become cost effective to employ RP techniques in many artistic applications. Taking into account the accuracy of art models and the RP materials available, the technological capabilities of concept modellers are more than adequate for the majority of art applications.

The two examples described below demonstrate the use of RP techniques in art. These were part of work conducted within the CALM (creating art with layer manufacture) project [**48**], which was supported by the Higher Education Funding Council for England as part of an initiative to promote the use of information technology (IT) within the art and design community in UK higher education.

The first example is an artwork representing a splash spanning the inside of a plexiglass vitrine (Fig. 13). In its final installation, the RP model (Fig. 14) will be incorporated into a plexibox exactly the width of the splash itself.

The second example is a cybersculpture representing an artefact that cannot be created using any conventional methods. The initial intentions of the artist were to produce an RP pattern and then cast it in bronze. However, after the SLS model (Fig. 15) was built, it was immediately recognized that this model, in conjunction with the lace-like Moiré surface patterns, satisfies the project requirements [**48**].

3.5 Engineering analysis models

Computer aided engineering (CAE) analysis is an integral part of time-compression technologies. Various software tools exist, mainly based on finite element analysis (FEA), to speed up the development of new products by initiating design optimization before

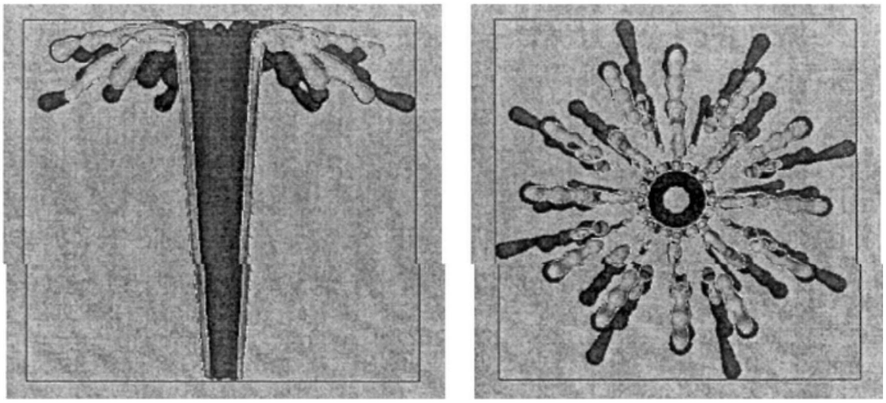


Fig. 13 Cross-sections of the three-dimensional model of a water splash. (Courtesy of M. Harris and the CALM project [**48**])

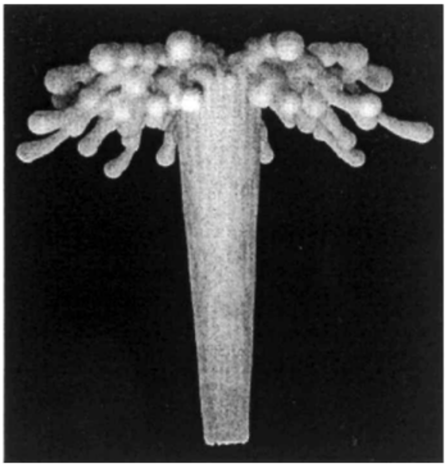


Fig. 14 SLS model representing a water splash. (Courtesy of M. Harris and the CALM project [**48**])

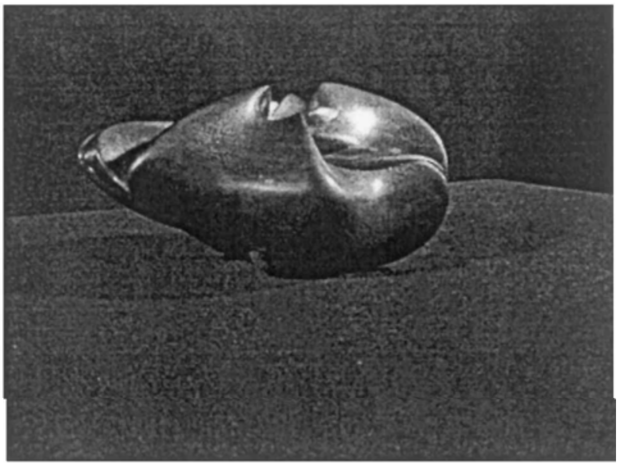


Fig. 15 SLS model of a cybersculpture. (Courtesy of K. Brown and the CALM project [**48**])

physical prototypes are available. However, the creation of accurate FEA models for complex engineering objects sometimes requires significant amounts of time and effort [**49–51**]. By employing RP techniques it is possible to begin test programmes on physical models much earlier and complement the CAE data. Four applications of RP models for engineering analysis are described below:

1. *Visualization of flow patterns*. SLA models were used to optimize the cross-flow jacket of a V6 high-performance racing engine (Fig. 16) [**50**]. Sixty sensors were installed in the model to monitor local flow temperature and pressure conditions. The coolant flow patterns were visualized by accurately injecting very small air bubbles. The flow patterns were recorded by high-speed video.
2. *Thermoelastic tension analysis (THESA)*. By employing the THESA method [**49**], RP models of real parts can be used on test rigs for structural analysis. This method allows temperature changes in the test parts to be directly correlated to the load. The effect of a particular load on the temperature patterns is analysed using thermal imaging.
3. *Photoelastic stress analysis*. Photoelastic testing is employed to determine the stresses and strains within physical parts under specific conditions. This method is based on the temporary birefringence of a transparent material subjected to a specific load [**50**]. SLA models exhibit the required birefringence that can be observed by irradiating the test samples with polarized white and monochromatic light. Results from photoelastic analysis of SLA models can be transferred to functional metal parts by employing fundamental similarity laws. It is also possible to 'freeze' the stresses and strains by warming the loaded model to a level above the resin glass transition temperature and then gradually cooling it back to room temperature (Fig. 17) [**50, 51**].
4. *Fabrication of models for wind tunnel tests*. RP techniques can be used to produce wind tunnel models, which are not subjected to significant loads

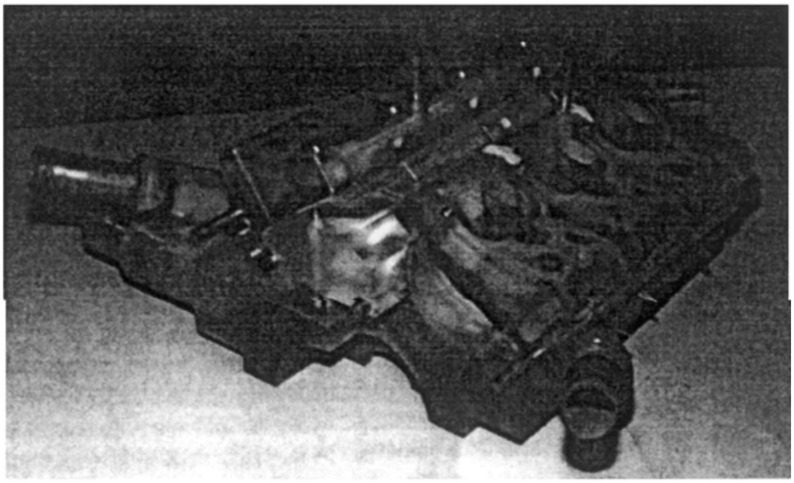


Fig. 16 Assembly of the cross-flow water jacket of a V6 high-performance racing engine [**50**]

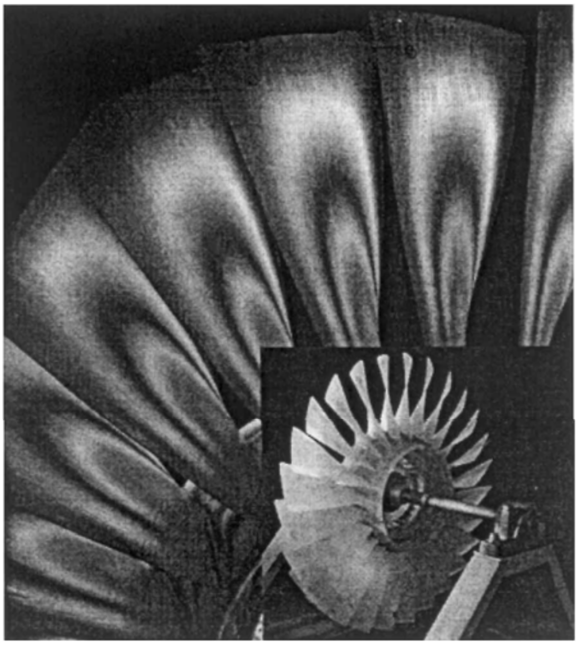


Fig. 17 The frozen stress distribution for a model of an aeroengine turbine rotor [**51**]

[**52**]. For example, the strength, accuracy and surface finish of models produced using SLA, SLS, FDM and SGC technologies are sufficient for tests of non-structurally loaded parts. In addition, SLS models produced using steel powder or metal models fabricated from RP patterns are adequate for lightly loaded applications.

4 RAPID TOOLING

As RP becomes more mature, material properties, accuracy, cost and lead-time have improved to permit it to be employed for the production of tools. Some traditional tool-making methods based on the replication of models have been adapted and new techniques allowing tools to be fabricated directly by RP have been developed. This section reviews indirect and direct methods for RT that are, or shortly will be, available for production runs of up to several thousand parts.

4.1 Indirect methods for rapid tool production

Indirect RT methods are alternatives to traditional mould-making techniques. These less expensive methods with shorter lead-times allow tool validation to be conducted before changes become very costly. The aim of these RT methods is to fill the gap between RP and hard tooling by enabling the production of tools capable of short prototype runs. The broad range of indirect RT solutions makes it difficult to determine the most appropriate method for a particular project. Companies need to know all of the available processes and have a clear understanding of their strengths and weaknesses together with the relative merits of the various materials they employ. A brief description of the most widely employed indirect methods is provided below:

1. *Metal deposition*. This process involves using an RP model with a good surface finish that incorporates a draft angle and an allowance for the shrinkage of the moulding material. The pattern is embedded along its parting line into plasticine within a chase. The sprue, gates and ejector pins are added and, after the exposed half of the mould is coated with a release agent, a 2–3 mm thick shell of a low-temperature molten metal is deposited over it. Once a metallic shell has been created, water cooling lines can be added and the shell is backfilled with epoxy resin or ceramic to improve the strength of the mould. These materials are selected because their coefficient of thermal expansion is close to that of the nickel or zinc

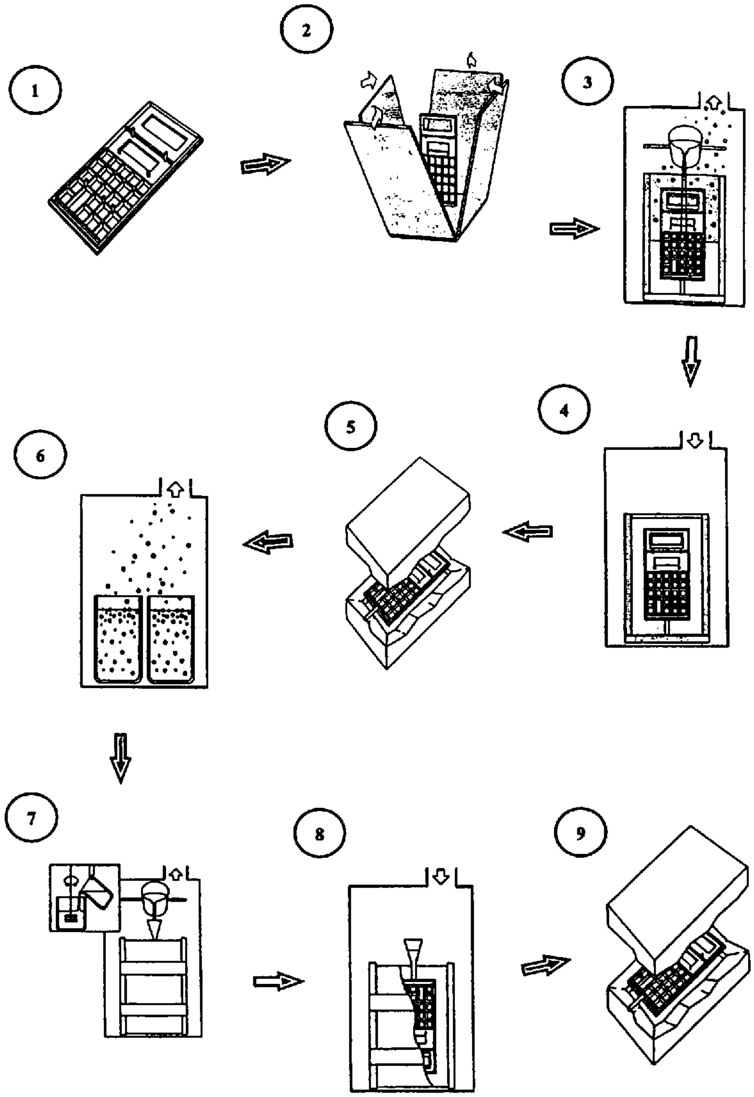


Fig. 18 Vacuum casting process. (Courtesy of MCP)

from which the shells are made. Aluminium powder is usually mixed with the epoxy resin or the ceramic to increase the thermal conductivity. After the backfilling material is cured, it is machined flat. The second half of the tool is built following the same procedure [**50, 53**].

2. *Room temperature vulcanizing (RTV)*. This process is an easy, relatively inexpensive and fast way to fabricate prototype or pre-production tools. RTV tools are also known as silicone rubber moulds. The most widely used form of RTV moulding is *vacuum casting*. The vacuum casting process includes the following main steps, as shown in Fig. 18 [**53**]:
   (a) producing a pattern (any RP method can be employed);
   (b) adding venting and gating to the pattern;
   (c) setting-up the pattern on the parting line and then suspending it in a mould casting frame;
   (d) pouring a deaerated silicone rubber into the casting frame around the pattern;
   (e) curing the mould inside a heating chamber;
   (f) removing the pattern from the silicone mould by cutting along the parting line and then closing and sealing the mould;
   (g) pouring a urethane resin into the mould inside a vacuum chamber;
   (h) curing the part in a heating chamber for 2–4 hours and then removing it from the mould;
   (i) cutting off the gate and risers from the casting to make an exact copy of the pattern.

   This process is best suited for projects where form, fit or functional testing can be done with a material that mimics the characteristics of the production material.
3. *Epoxy tooling*. This process is used for manufacturing prototype parts or limited runs of production parts. Epoxy tools are used as [**53**] moulds for prototype plastic injection, moulds for castings, compression

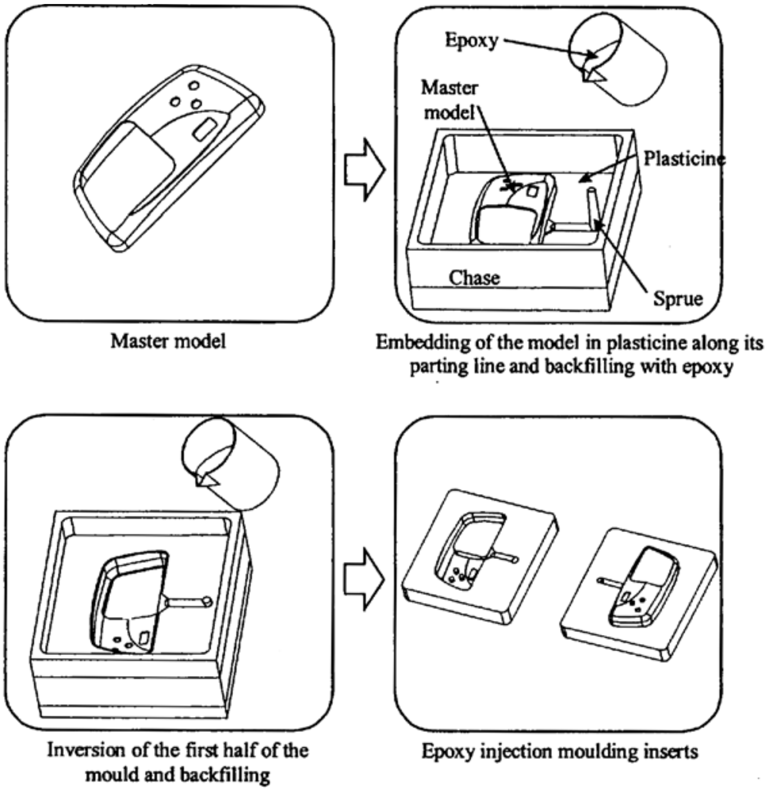


Fig. 19 Epoxy mould

moulds and reaction injection moulds. The fabrication of the mould begins with the construction of a simple frame around the parting line of the RP model (Fig. 19). Sprue gates and runners can be added or cut later on, once the mould is finished. The exposed surface of the model is coated with a release agent and epoxy is poured over the model. Aluminium powder is usually added to the epoxy resin and copper hose cooling lines can also be placed at this stage to increase the thermal conductivity of the mould. Once the epoxy has cured, the assembly is inverted and the parting line block is removed, leaving the pattern embedded in the side of the tool just cast. Another frame is constructed and epoxy poured to form the other side of the tool. When the second side of the tool is cured, the two halves of the tool are separated and the pattern is removed [**54**].

4. *Ceramic tooling.* Instead of epoxy, any plaster ceramics can also be cast around a master to produce a tool cavity. Ceramic tools can be employed in plastics processing, metal forming and metal casting [**55**]. In making ceramic tools, the amount of water used has to be controlled to avoid excessive shrinkage as the material sets. Recently, attention has been focused on non-shrinking ceramics. These calcium silicate-based castable (CBC) ceramics were initially developed for applications where metal spraying was not suitable.
5. *Spin casting.* This process consists of injecting a material through a central sprue into a mould that is rotated at high speed. Spin casting moulds for metal parts are made of heat-vulcanized silicone. The heat that is given out during the fabrication of such moulds is too high for most RP patterns. For this reason, the fabrication of a metal part using spin casting consists of several steps. First, an RTV rubber mould is made from the RP master. From this mould, a tin-based metal alloy part is cast and is used as a model for the fabrication of a heat-vulcanized silicone mould [**56**]. This final mould can produce spin-cast zinc alloy parts that have similar physical strength properties to both die cast aluminium parts and die cast Zamak zinc parts [**57**].
6. *Investment casting* [**2**]. This process is used to cast complex and accurate parts. Wax patterns are employed to define the part shape and then are melted away. It is also possible for patterns to be produced from foam, paper, polycarbonate and other RP materials that can be easily melted or vaporized. Two forms of this process are known, shell investment casting and solid flask investment casting. The latter employs solid flask moulds instead of shells. In addition, the moulds are filled under a vacuum differential.

7. *Fusible metallic core* [2]. Fusible metallic core technology is a new method for forming complex, hollow, one-piece plastic components that may be difficult to produce by any other method. This technology can be considered as a variation of investment casting. The difference between the two processes is in the material of the sacrificial patterns employed. In particular, low melting point alloys are used instead of wax. RP techniques can be applied to build part and core models that assist in fabricating the casting dies to make the cores. The fusible cores must have the internal shape of the part. Usually, the core is designed to be placed into a suspended position in the mould and is contained within the mould. The moulded parts encapsulate the removable cores that are melted away by induction heating or by immersing the mouldings in hot water or oil. Cores can have a melting point of up to 220 °C depending on the alloys used.
8. *Sand casting*. The sand casting process is often employed for the production of relatively large metal parts with low requirements for surface quality. RP techniques can be utilized to create master patterns for fabricating sand moulds. These moulds are produced by placing RP patterns in a sand box which is then filled and packed with sand to form the mould cavity. When employing RP techniques, it is easy to build patterns that include compensation for the shrinkage of the castings as well as additional machining stock for the areas requiring machining after casting. The other benefits of employing RP techniques are significantly reduced lead-times and increased pattern accuracy.
9. *3D Keltool™ process*. This process is based on a metal sintering process introduced in 1976. The 3D Keltool™ process converts RP master patterns into production tool inserts with very good definition and surface finish. It includes the following steps [58]:
   (a) fabricating master patterns of the core and cavity;
   (b) producing RTV silicone rubber moulds from the patterns;
   (c) filling the silicone rubber moulds with a mixture of powdered steel, tungsten carbide and polymer binder with particle sizes of around 5 μm to produce 'green' parts (powdered metal held together by the polymer binder) duplicating the masters;
   (d) firing the 'green' parts in a furnace to remove the plastic binder and sintering the metal particles together;
   (e) infiltrating the sintered parts (70 per cent dense inserts) with copper in a second furnace cycle to fill the 30 per cent void space;
   (f) finishing the core and cavity.

   The material properties allow inserts produced using this process to withstand more than 1 000 000 moulding cycles.

Indirect tooling methods are intended as prototyping or pre-production tooling processes and not production methods. Consequently, tools fabricated employing these methods will exhibit differences compared to production tools, e.g. larger draft angles, simpler part shapes and lower mechanical and thermal specifications. These differences affect the production cycle time, the part mechanical properties and the tool life. However, the aim of these tooling methods is generally not to replace production tooling but to make only up to a few hundred parts; therefore these tools do not require the strength for a long life. For the same reason, they do not need to be as efficient as production tools and it is justifiable to adopt a longer cycle time per part to compensate for poor thermal conductivity.

4.2 Direct methods for rapid tool production

Indirect methods for tool production as described in the previous section necessitate a minimum of one intermediate replication process. This might result in a loss of accuracy and could increase the time for building the tool. To overcome some of the drawbacks of indirect methods, some RP apparatus manufacturers have proposed new rapid tooling methods that allow injection moulding and die-casting inserts to be built directly from three-dimensional CAD models.

Direct RT methods enable the production of inserts capable of surviving from a few dozen to tens of thousands of cycles and represent good alternatives to traditional mould-making techniques. The durability or life expectancy of the inserts produced by these methods varies significantly, depending on the material and the RT method employed. This makes the application area of direct RT processes also very wide, covering prototype, pre-production and production tooling. According to their application, direct RT processes can be divided into two main groups.

The first group includes less expensive methods with shorter lead-times that are appropriate for tool validation before changes become costly. Direct RT methods that satisfy these requirements are called methods for 'firm tooling' (also known as 'bridge tooling' [58]). RT processes for *firm* tooling fill the gap between *soft* and *hard* tooling, producing tools capable of short prototype runs of approximately fifty to a hundred parts using the same material and manufacturing process as for final production parts.

The second group includes RT methods that allow inserts for pre-production and production tools to be built. RP apparatus manufacturers market these methods as 'hard tooling' solutions [58]. Currently available solutions for 'hard tooling' are based on the fabrication of sintered metal (steel, iron and copper) powder inserts infiltrated with copper or bronze (DTM RapidTool™

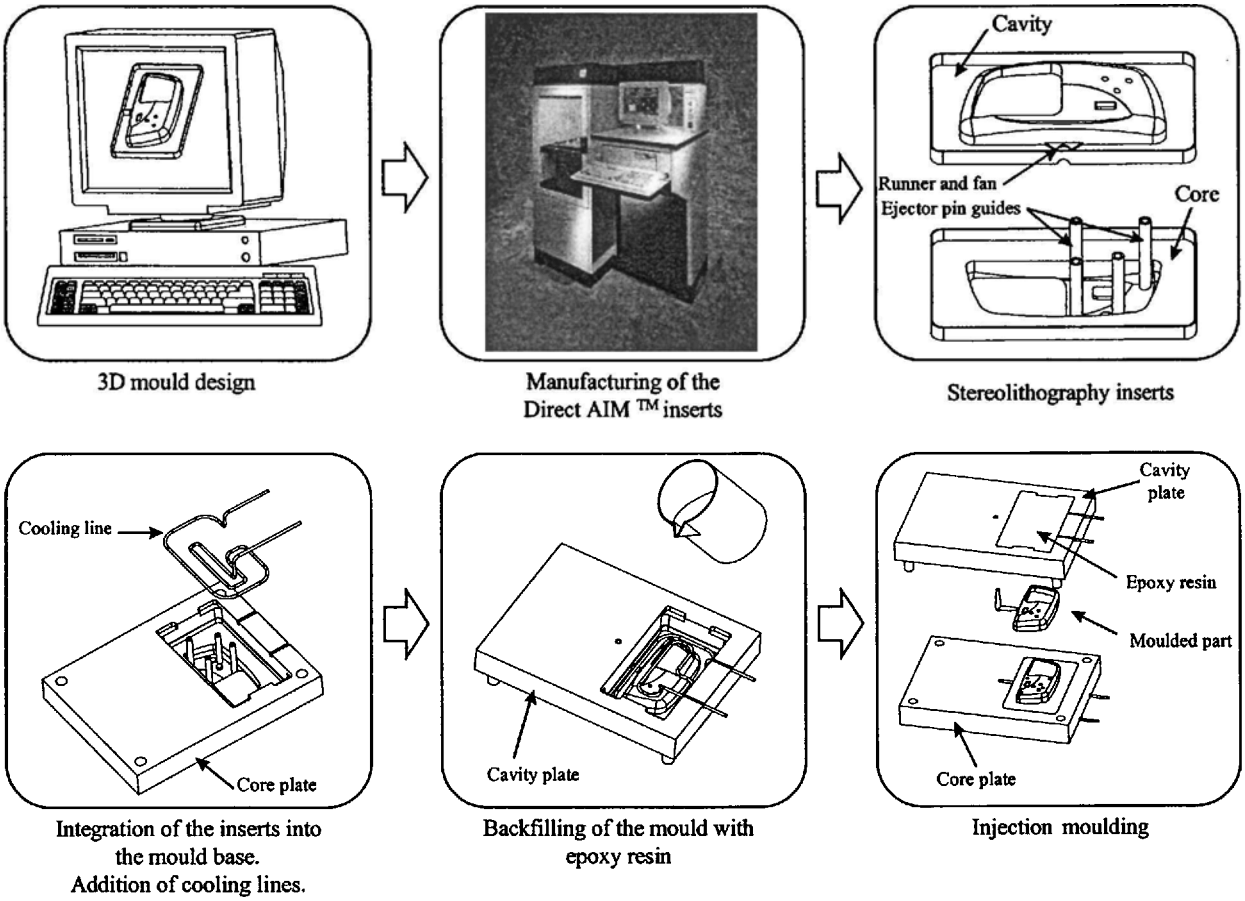


Fig. 20 Direct AIM™ injection mould

process, EOSINT metal from EOS, three-dimensional printing of metal parts from Soligen).

The most popular direct RT methods are presented below:

1. *Direct ACES™ Injection Moulds (AIM™)*. With this method, SL is used to produce epoxy inserts for injection mould tools for thermoplastic parts (Fig. 20) [**2, 15, 59**]. Because the temperature resistance of the curable epoxy resins available at present is only up to 200 °C (Cibatool® SL5530HT) and thermoplastics are injected at temperatures as high as 300 °C (572 °F), specific rules apply to the design and production of this type of injection moulding inserts [**60**]. Runners, fan gates and ejector pin clearance holes are added to the CAD model and the inserts are shelled to a recommended thickness of 1.27 mm (0.05 inch). The inserts are then built using the accurate clear epoxy solid (ACES) style [**50**] on an SL machine. The supports are subsequently removed and the inserts are polished in the direction of the draw to facilitate part release. To remove the maximum amount of heat from the tool and reduce the injection moulding cycle time, copper water cooling lines are added and the back of the inserts is filled with a mixture made up 30 per cent by volume of aluminium granulate and 70 per cent of epoxy resin. The cooling of the mould is completed by blowing air on the mould faces as they separate after the injection moulding operation. To increase both the resistance to erosion and the thermal conductivity of Direct AIM™ tools, the deposition of a 25 μm layer of copper on the mould surface has been investigated [**58**].
2. *Laminate tooling*. The original LOM process produces parts with a wood-like appearance using sheets of paper. Experiments to build moulds directly or coated with a thin layer of metal have been reported [**61**]. Unfortunately, moulds built in this way can only be used for low-melting thermoplastics and are not suitable for injection moulding or blow moulding of common thermoplastics. For this reason, new materials based on epoxy or ceramic capable of withstanding harsh operating conditions have been developed. The polymer composite process is being investigated and the first industrial application is expected in the near future. The ceramic process is less advanced and requires more software and hardware modifications to the LOM machine. Few results for these processes are available but current

indications are promising. In addition, attempts have been made to use unbonded laminate tooling for pressure die casting [**62**]. In this case, the prototype tools are fabricated by clamping together laser-cut profiles in tool steel sheets.

3. *RapidTool*™ *process.* This process employs SLS to build tooling inserts. The latest materials developed for the RapidTool process of producing metal parts by SLS are LaserForm™ and copper polyamide(PA). Each of these materials requires different processing techniques:
   (a) *LaserForm*™ [**63**]. This is a powder made of 420 stainless-steel-based particles, coated with a thermoplastic binder. The processing of LaserForm can be broken down into two main stages [**63**]. During the first stage (the 'green' stage), tooling inserts are built layer by layer through fusion of the binder in an SLS machine. In the second stage (oven cycle), the green part is converted into a fully dense metal part by infiltration with molten bronze. During the oven cycle, between 450 and 650 °C the polymer evaporates and at 700 °C the sintering of the remaining steel powder begins. Then the inserts are heated up to 1070 °C where bronze infiltration occurs driven by capillary action. To avoid oxidation of the steel surfaces, all processing is done in a nitrogen atmosphere. The final LaserForm inserts are 60 per cent stainless steel and 40 per cent bronze fully dense parts, which can be finished by any technique, including surface grinding, milling, drilling, wire erosion, EDM, polishing and surface plating.
   (b) *Copper PA* [**64**]. This is a metal–plastic composite designed for short-run tooling applications involving several hundred parts (100–400 parts) from common plastics. At the CAD stage, the inserts are shelled and cooling lines, ejector pin guides, gates and runners are included in the design to be built directly during the SLS process. No furnace cycle is required and unfinished tool inserts can be produced in a day. Only subsequent finishing is necessary before integration of the inserts in the tool base. This includes sealing of the insert surfaces with epoxy, finishing them with sandpaper and finally backing up the shell inserts with a metal alloy. The cycle times of moulds employing copper PA inserts are similar to those for metal tooling.

   Development efforts have been directed towards insert design optimization [**2**], increasing heat transfer rates by producing inserts with conformal cooling channels [**65**] and refining insert finishing techniques [**2**].
4. *SandForm*™ *tooling.* SandForm™ zirconium and silicon materials can be used to build moulds and cores directly from three-dimensional CAD data employing the SLS process [**2**]. The sand moulds and cores produced are of equivalent accuracy and have properties that are identical to those of moulds and cores fabricated with conventional methods. SandForm™ moulds and cores can be used for low-pressure sand casting.
5. *EOS DirectTool*™ *process* [**66**]. This process uses proprietary metal powders that are selectively sintered in a specially developed machine. The sintered parts are porous and usually must undergo infiltration with an epoxy resin in order to increase their strength [**66**]. After infiltration, further polishing of the part surfaces is possible to achieve the quality required for injection moulding inserts. The DirectTool™ process is mainly utilized for rapidly producing complex inserts, the surfaces of which cannot be machined directly. The process is a viable alternative for prototype and pre-production tooling applications, requiring the manufacture of up to a few thousand parts in common engineering plastics.
6. *Direct metal tooling using 3DP*. This RT process uses 3DP to build tooling inserts in a range of materials including stainless steel, tungsten and tungsten carbide. The process allows the fabrication of parts with overhangs, undercuts and internal volumes as long as there is an escape route for the unused loose powder. The production of metal parts includes the following steps:
   (a) building the parts by combining powder and binder employing the 3DP process;
   (b) sintering the printed parts in a furnace to increase their strength;
   (c) infiltration of the sintered parts with a low melting point alloy to produce fully dense parts.

   The 3DP process can be easily adapted for production of parts in a variety of material systems, e.g. metallic/ceramic compositions with novel material properties [**24, 67**].
7. *Topographic shape formation (TSF)*. This process is very similar to 3DP. This technology is used primarily for the rapid production of moulds. Parts are built by successive layering of a silica powder and selective spraying of paraffin wax from an X–Y–Z controlled nozzle. The wax binds the powder to form a new cross-section of the part and also partially melts the previous layer to ensure good adhesion. Once a part is completed, it is sanded, coated in wax and then employed as a mould for the customer's component. Materials in use include concrete, fibreglass and expanding foam [**68**].

Direct methods for tool production reduce the total production time and the inaccuracies introduced by intermediate replication stages. The restricted range of materials available is still the most severe drawback of direct tooling methods, but materials are continually improving and new materials are regularly becoming available. Special attention should be paid to the specific design and finishing requirements of RT inserts because these aspects critically affect the capabilities of the process [**69, 70**]. A promising direction for further improvement of direct tooling methods is to combine their capabilities with those of traditional tooling methods. In this way, the application area of direct tooling methods can be extended significantly.

5 APPLICATIONS OF RAPID TOOLING TECHNOLOGY

The introduction of RT technology has enabled prototype, pre-production and in some cases full production tooling to be fabricated within significantly reduced time frames. A sound understanding of the capabilities and limitations of RT processes is essential in order to implement the technology successfully.

This section presents three examples illustrating the application of the RapidTool™ process, one of the most developed direct RT methods, to aluminium gravity die casting, plastics injection moulding and production of metal parts:

1. *Die casting inserts*. To evaluate the applicability of RapidTool™ to aluminium gravity die casting, inserts for a windscreen wiper arm were built (Fig. 21). The inserts were finished following the steps described in reference [**2**]. One of the bosses at the end of the wiper was used as a reference feature to achieve good matching of the two halves of the tool. The tool was used to cast parts in LM6 aluminium alloy. After producing 250 castings in four separate runs, no degradation signs were visible on the insert surfaces or on the cast parts. The tests showed that RapidTool™ dies can be utilized for production of low- to medium-size batches of castings. Given the quality of the die material, it is estimated that over five thousand castings could easily be produced from the dies.

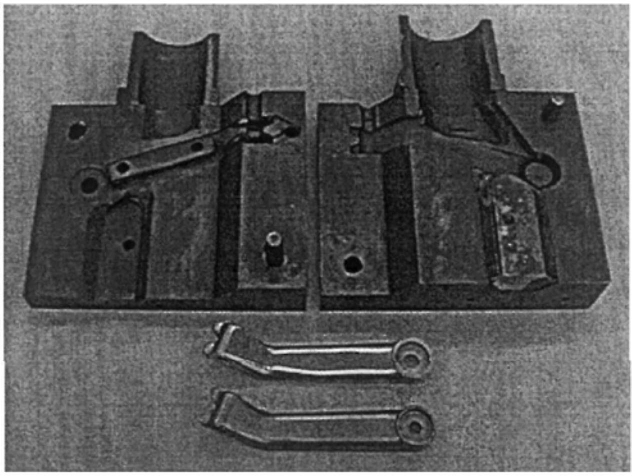
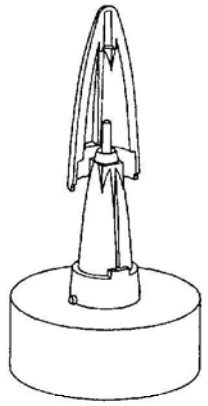


Fig. 21 Die casting tool produced from RapidTool™ inserts

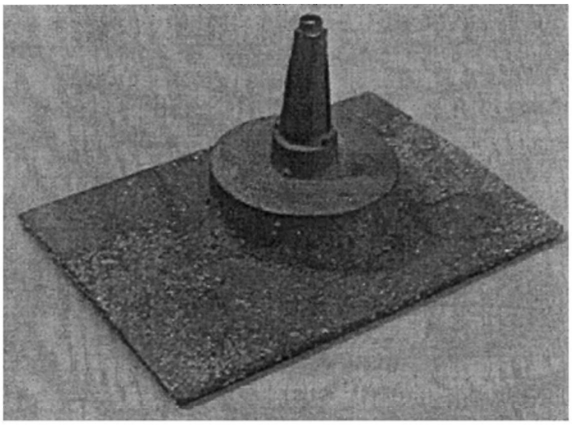
2. *Injection moulding inserts*. This example illustrates the capability of the RapidTool™ process for fabrication of injection moulding inserts. An insert was manufactured for moulding the cap for a nose hair trimmer. While the external surface of the part is relatively simple, its internal features are much more complex. The internal surface of the cap consists of a cone that transforms progressively into a square hole. The hybrid approach adopted was to machine the mould conventionally from steel and to make the core using the RapidTool™ process. As shown in Fig. 22, the RapidTool core was built without the protruding pin. This feature was judged to be too small and weak to be reproduced reliably by the RapidTool™ process. Because of its simple shape, the pin was machined from steel and added later to the insert. The tool thus manufactured by combining the capabilities of conventional tooling techniques and the RapidTool™ process was successfully used to produce several hundred mouldings in ABS.
3. *Metal parts: car seat frame*. The RapidTool™ process can also be used directly to build complex metal parts [**69, 70**]. However, it must be borne in mind that the parts in their intermediate green stage are very fragile and must be handled with great care. Another problem is that, in contrast to moulding inserts, such parts do not normally have flat bases that can be used for infiltration during the furnace cycle. As an example of what could be achieved, a frame for a seat was fabricated using LaserForm. Given its size, the frame was built in four pieces. Figure 23 shows one of these pieces. In order to produce it, its thickness was first increased to give more strength to the part during the green stage. Then a base and some support structures were added before building the part using the SLS process. These support structures have two main functions. The first is to prevent distortion or breakage of the part during the cleaning and sintering stages. The second is to facilitate the infiltration of the part during the furnace cycle. Finally, the four pieces were brazed together and the support structures were machined off.

6 FUTURE TRENDS

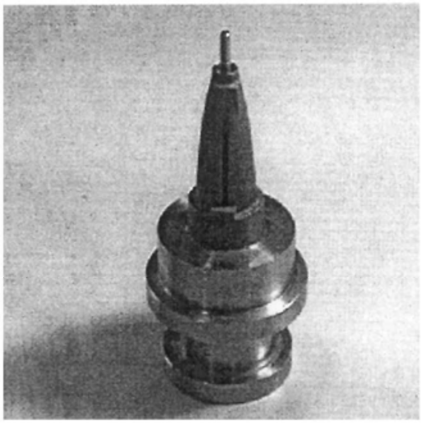
Research in the fields of RP and RT is just over 10 years old. In spite of this, significant progress has been made in widening the use of these technologies and in the development of new processes and materials. To achieve long-term growth in these fields and realize their full potential, a number of challenges remain. These challenges could be grouped under the following categories:



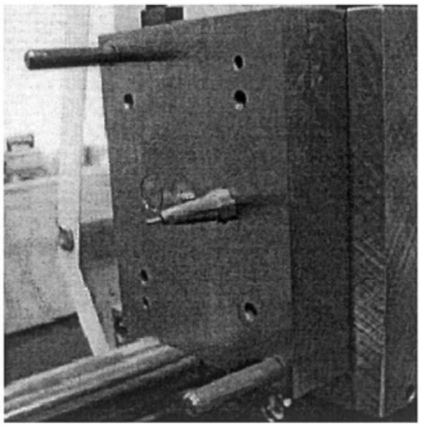
(a) Core and Cavity



(b) RapidTool core



(c) Finished Core



(d) Core mounted in injection moulding bolster

Fig. 22 Building stages of the cap insert (three-dimensional design, infiltration, finishing, integration)

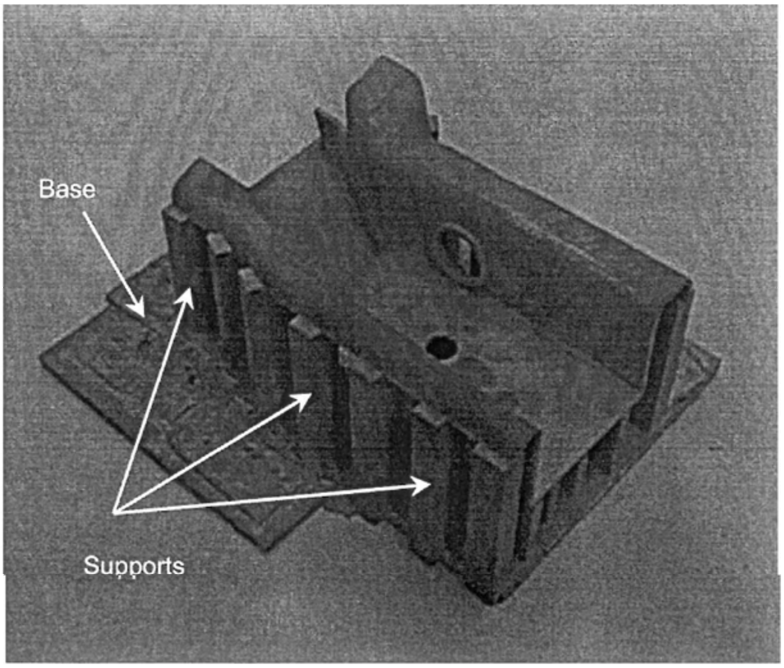


Fig. 23 One part of the frame after the furnace cycle

1. *Productivity/cost of RP machines.* To benefit truly from the 'direct' fabrication capabilities of RP processes, especially when the serial production of parts is targeted, their productivity should be increased and machine costs reduced significantly. Currently, there are two main approaches to addressing these issues. With the first approach, productivity is raised by increasing the number of channels used for data transfer (multiple one-dimensional channels) without modifying the working principles of a process. The second approach is to develop a new generation of RP machines that are specially designed for serial production and employ new mechanisms for data transfer (multiple/arrays of one-dimensional channels or two-dimensional channels) and/or new physical principles. It is expected that long-term growth in the RP industry will come from applications that are impossible/very difficult, costly and time consuming to implement with conventional manufacturing techniques. Therefore, new RP machines should address the specific requirements of these applications. For example, these new machines should allow improved accuracy and surface finish of RP parts, multi-axis deposition of material, direct building of multi-component assemblies [**71**], fabrication of materially graded structures (in density and composition) and manufacture of mesoscopic components and devices. Furthermore, it is expected that wider use of RP machines for rapid manufacturing would lead to reduction of their cost.
2. *Materials.* One of the main limitations of RP processes is the limited variety of materials and their properties, and also their relatively high cost. Significant research efforts are focused on the development of a broader range of materials that simulate very closely the properties of the most commonly used engineering plastics. In particular, much research is being conducted on the development of new materials with high rigidity, high impact strength and high tensile elongation at breaking. Also, a range of materials for fabrication of investment casting patterns with low ash content, high impact strength and good surface finish are currently under development. Recently, the fabrication of multi-materials and heterogeneous objects has attracted the attention of the research community. This is quite understandable because RP is well suited to building such objects. Functionally gradient components could be manufactured from different constituent materials exhibiting continuously varying composition and/or microstructure. Developments in this area will make possible the fabrication of objects with multiple and conflicting functionality. Progress in the area is directly linked with the development of new CAD tools that are suitable for designing heterogeneous objects.
3. *Process planning.* Although process plans for building complex RP parts are reduced to containing only three operations (these usually being building parts, inspection and finishing, which can include painting) compared to the many steps required by conventional material removal processes, the process planning tasks associated with layer manufacturing require special attention. These tasks include selecting the part orientation, identifying the support structures needed, slicing and deposition path planning and the specification of process parameters. Existing approaches to addressing these problems fall into two categories: algorithmic and decision-support solutions [**72**]. The algorithmic approach relies on geometrical reasoning mechanisms to find solutions for these tasks. For example, this approach is used to determine the part orientation in respect of some user-defined criteria (minimization of the support structures required, avoidance of trapped volumes, improving part quality and engineering properties), to study the influence of different deposition patterns and process parameters on part properties, to identify overhanging features requiring support structures utilizing STL file facets, solid models or slice data, and to develop new techniques for slicing (adaptive slicing and slicing of heterogeneous objects). The second approach employs decision-support methods to perform tasks that require quantifying the trade-offs between competing goals. Such process planning methods employ multi-criteria optimization techniques, analytical models and heuristics [**73**]. With increases in part complexity and the wide range of available RP materials and RP machines, there is a need for more advanced process planning tools, in particular tools that could relate process variables to part quality characteristics and address the process-specific requirements associated with the fabrication of parts from heterogeneous materials.
4. *RP data formats and design tools.* The stereolithography (STL) format was introduced in the early years of RP technology and is considered a de facto standard for interfacing CAD and RP systems. The STL format has a number of drawbacks [**74**] that are inherent in the representation scheme employed. The use of other standard formats for product data exchange such as IGES, HPGL, STEP and VRML have been considered in place of STL, but as problems remain these alternative formats are not widely accepted. Work on the development of new formats continues in order to address the growing requirements of RP and RT applications for more precise methods of data representation. Also, in recent years, with the emergence of RP processes for fabrication of heterogeneous objects, there is an increasing interest within the research community in developing new CAD tools that enable objects with varying material composition and/or microstructure

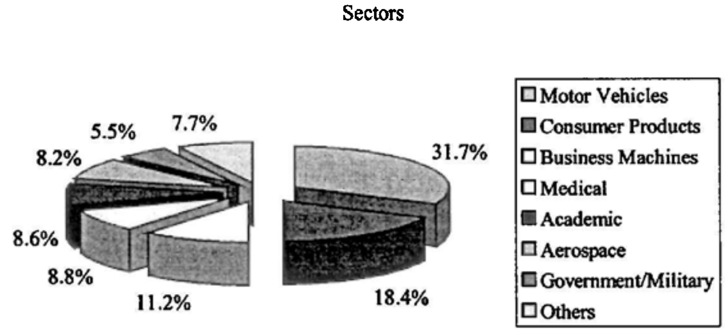


Fig. 24 The use of RP systems in different sectors [**79**]

to be designed [**72**]. Currently, a number of CAD systems for constructing such objects are under development employing voxel-based methods [**75**], generalized cellular decomposition [**76**], finite element based methods [**76, 77**] and constructive methods [**78**]. As already mentioned, advances in this area are directly linked to research and development in technologies capable of producing materially graded structures.

7 CONCLUSIONS

The remarkable increase in the number of commercially available RP and RT solutions of the 1990s can be explained by advances in three-dimensional CAD modelling, computer aided manufacturing, computer numerical control and the development of new materials. These technologies were used initially in the fast growing, highly competitive, high technology, automotive and aerospace industries, which generated added momentum. In the first part of the last decade, the annual growth in sales of RM systems approached 40–50 per cent. In the last few years, the same rapid growth has not continued. However, developments in this area still attract significant interest and in the last two years alone 208 new patents were filed. In 1999, sales growth was 22 per cent and it was estimated that 3.4 million parts were built world wide using RP technologies [**79**]. Another important aspect is that the application of RP and RT has extended to other sectors of the economy (Fig. 24). This strong and consistent growth in sales and the widespread use of the technology present very optimistic prospects for the future of rapid manufacturing.

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