OCCASION

This publication has been made available to the public on the occasion of the 50th anniversary of the United Nations Industrial Development Organisation.

DISCLAIMER

This document has been produced without formal United Nations editing. The designations employed and the presentation of the material in this document do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations Industrial Development Organization (UNIDO) concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries, or its economic system or degree of development. Designations such as "developed", "industrialized" and "developing" are intended for statistical convenience and do not necessarily express a judgment about the stage reached by a particular country or area in the development process. Mention of firm names or commercial products does not constitute an endorsement by UNIDO.

FAIR USE POLICY

Any part of this publication may be quoted and referenced for educational and research purposes without additional permission from UNIDO. However, those who make use of quoting and referencing this publication are requested to follow the Fair Use Policy of giving due credit to UNIDO.

CONTACT

Please contact publications@unido.org for further information concerning UNIDO publications.

For more information about UNIDO, please visit us at www.unido.org

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Tel: (+43-1) 26026-0 · www.unido.org · unido@unido.org

ADVANCES IN MATERIALS TECHNOLOGY MONITOR

Vol. 2, No. 1, 1995

CONTENTS

UNIDO's *Advances in Materials Monitor* is established as a mechanism of current awareness to monitor developments in the materials sector and to inform governments, industry and academia, primarily in developing countries.

Technical Editor: Vladimir Kojarnovitch
Compiling and editing: Joan Roetzer-Sweetland
Editorial Board: V. Podshibyakin, N. Biering, H. Yalcindag, A. Bromley, E. Vento

Published in 1995 by the United Nations Industrial Development Organization (UNIDO)
Vienna International Centre
P.O. Box 300
A-1400 Vienna
Austria
Tel: (43-1) 21131-0
Fax: (43-1) 21131-6843
E-mail: vkojarnovitch@unido.org
jroetzer-sweetland@unido.org

ISSN 1020-2978

TO OUR READERS

Industry's catalytic role in the development process is changing in response to the new global pattern of rapid and accelerating technological change, sweeping trade liberalization, far-reaching deregulation of markets - including the privatization and commercialization of state-owned enterprises - and the globalization of international business. Consequently, the pattern and nature of industrialization have changed radically over the past two decades, with far-reaching implications for national industrial policy and for corporate strategies at the enterprise level. In the Uruguay Round era, economic decision-making, at national and firm level, is increasingly influenced by cross-border considerations. National markets are being regionalized, and national firms are increasingly being challenged by foreign rather than domestic competitors as the progressive implementation of the Uruguay Round Agreements means that trade barriers are lowered.

Competitiveness will increasingly depend on the strategy and management of enterprises and on the manner in which entrepreneurs and managers perceive their industry, the role of their enterprise in a competitive, global market and their ability to take initiative in specific, changing situations. The crucial role of processing technology for the competitiveness of firms in global markets has to be viewed in terms of not only entry to such markets, but also of their capability to continually remain in them. The competitiveness of enterprises in the medium- and long-term is often a direct result of their ability to learn continuously and to build - at lower cost and more rapidly than competitors - the core capabilities that enable them to generate new products, services and value-added activities in the shortest possible time.

Due to the world-wide competitive situation, interest in new methods, business practices and technologies to improve and accelerate product development, have increased continuously over the last few years. Production benefits in industry have been obtained with such techniques as simultaneous engineering and total quality management and CAD, CAM, CAP and NC technologies. In product development, rapid prototyping and rapid product development have proven to be the instruments to save time and money and develop innovative products.

It is clear that flexible manufacture, increased automation, rapid prototyping and associated software have emerged as essential technological features of manufacture in industrialized countries and that this process will be further extended during the next decade. To the extent that such technologies are gradually extended in developing countries, substantial changes in structures will be required for the management of technology at the enterprise level, together with policy and institutional support at the initial stages. All these technologies are shortening the time between the design of a new product and its manufacturing thus speeding up their appearance on markets.

Many of our readers will be interested in knowing that all the Monitors will soon be available on the Internet. The UNIDO World Wide Web (WWW) server (http://www.unido.org) was opened to public access on 24 November 1995, with some 140 documents available so far. Any document may be located via an integrated full text searching facility. Interaction is made possible by a growing number of on-line forms and clickable e-mail addresses provided in every document. The system has been designed to accommodate by e-mail a delivery service at a future stage of development.

Vladimir Kojarnovitch
Technical Editor

(i) 18p.
tables
graphs
diagrams
illus.

ADVANCES IN MATERIALS TECHNOLOGY MONITOR

VOLUME 2, NUMBER 1, 1995

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

Vienna, 1995

CONTENTS

A. LEAD ARTICLE

RAPID PROTOTYPING AND NEW MATERIALS

Dipl.-Phys. Martin Geiger
Fraunhofer-Institut für Produktionstechnik
und Automatisierung (IPA), Stuttgart, Germany

1. *Introduction*

Due to the world-wide competitive situation, interest in new methods, business practices and technologies to improve and accelerate product development have increased continuously over the last few years. Production benefits in industry have been obtained with such techniques as simultaneous engineering and total quality management and CAD, CAM, CAP and NC technologies. In product development, rapid prototyping and rapid product development have turned out to be the instruments to save time and money and develop innovative products.

Beginning in the late 1970s, new technologies have been developed aimed at improving and hastening the manufacturing time of prototypes. Contrary to other automated fabrication technologies in use, the basic principle of these new technologies is an additive process, where an object is built by joining particles or layers of material. Conventional automated prototyping normally uses subtractive processes such as NC milling or grinding. The first commercial apparatus was presented at the AUTOFACT show in Detroit (USA) in 1987 and was based on selectively curing a surface layer of photopolymer using a laser and building three-dimensional objects with successive layers. Up to 1990, about 150 commercial machines based on stereolithography were sold before the first new additive fabricators such as fused deposition modeling, laminated object manufacturing, solid ground curing and selective laser sintering came on the market. At that time, the systems were relatively inaccurate and the choice of materials limited, but it was possible to manufacture prototypes in days instead of months. Therefore, first applications and benefits were possible in rapidly manufacturing prototypes of low quality, which were used for design tests and as acquisition and communication tools. According to these abilities, the additive processes were given the term "rapid prototyping".

These technologies set the starting-point for a lot of research and development activities at universities, research centres and industrial enterprises. The additive technologies have taken enormous strides and rapid prototyping became a magic formula in industrial product development. During the last few years the understanding of rapid prototyping has constantly changed, which is best represented in the proceedings of international events of rapid prototyping. Up to 1991, most representations at rapid prototyping conferences reported on new additive processes and improvements of systems. Nowadays, a lot of additional technologies including subtractive, e.g. fast NC-milling and compressive principles (casting, moulding and forging) to rapidly produce prototypes and a wide range of applications for different branches of industry, are the content of these conferences. In a period of only a few years rapid prototyping has changed from a number of inaccurate technologies widely met with a pitying smile, to a mighty significant tool. Now it is hard not to imagine that it is not used in the automotive industry and related branches.

Some years ago there were only a handful of processes under development and the rapid prototyping R&D family was quite small. Nowadays, R&D activities on rapid prototyping are located at a large number of universities and research centres and the number of additive fabricators is still increasing, even if most processes have still not been commercialized. In addition to the rapid prototyping technologies, new methods of organization, cooperation and business practices using the rapid prototyping technologies are being developed, examined, tested and summarized under the term "Rapid Product Development".

The object of this article is to give an overview of the present state-of-the-art, commercial technologies, R&D activities and trends in rapid prototyping (RP) and rapid product development (RPD). Because RPD and RP originate from the additive fabricators (AF), principles, processes and machines of the different AFs and available accuracy and materials are discussed in more detail. Thanks are given to Bernd Keller of the Institut für Kunststoffprüfung und Kunststoffkunde (IKP) at the University in Stuttgart, who gave a lot of information on materials. Although an international view on rapid prototyping is intended, one should consider that the author is a European resident. Therefore, although practical experience was only made in Europe, a lot of knowledge arose from visits and contacts in the USA and much information is summarized from books, proceedings and articles. It is furthermore intended to give the reader a source to start their own investigations on RP to supplement the information given and to search for special information. Therefore, books considered as important, proceedings, annual international events and Internet addresses are listed without claiming to be complete.

2. *Fundamentals of additive fabricators*

In the late 1970s and early 1980s in Minneapolis and in California, several activities started in developing automated prototyping concepts based on selectively curing a surface layer of photopolymer and building three-dimensional objects with successive layers. The activities in California resulted in a complete system called stereolithography, which can automatically build detailed parts. The first stereolithography apparatus (SLA-1) was presented at the AUTOFACT Show in Detroit in November 1987. This was the start of the growing significance of new "additive fabricators" (AF), which are mostly published under the name "rapid prototyping", because of their ability to produce prototypes out of CAD data directly without a tool.

In the meantime, there are over 30 RP systems and related technologies under development. While the system accuracy and the material properties improved, more efficient system software, improved CAD systems and benefits of combination with conversion technologies such as vacuum casting and investment casting were developed.

thereby increasing the industrial use of these techniques considerably.

2.1 Working principle

Present commercial AFs allow the building of prototypes in a limited choice of materials. Most materials used are photosensitive polymers, nylon, polycarbonate, a wood-like material and some other plastics. Recent developments allow direct production in a metallic alloy. To obtain prototypes in other materials, post-processing such as surface finishing or sintering, or subsequent processes such as moulding or casting are necessary. Nevertheless, the number and quality of materials is increasing rapidly. The size of the process chambers of all systems is still below one metre in each direction. Larger objects have to be built as separate small parts and glued together afterwards.

3-D CAD data of an object is the common information source for AFs. Because all AFs build the objects layerwise, which means that material is added layer by layer, all machines need information on a number of parallel cross-sections of the objects at a given distance. Figure 2.1 shows the most commonly used procedure in preparing 3-D CAD data for AFs. In most cases the CAD data are converted into a neutral data format. In RP the STL format became a de facto standard for the representation of the 3-D geometry description of objects. The objects are represented by facets building an approximated closed description of the surface of the objects. Basic elements of the STL format are triangles with a normal vector. Most 3-D CAD systems include an STL interface. The STL file of an object is the input for a slice computer. The result is a number of parallel cross-sections. Each cross-section involves information where material has to be added. The distance to the following cross-section fixes the height of the single layer. Hence AFs could be seen as 3-D plotters. The slices serve to control the fabricator dependent on the actual principle.

A more detailed description of data preparation for AFs is given later. The different systems may be categorized by the different basic working principles as:

1. Selective hardening of photosensitive material by radiation;
2. Selective fusing or sintering powder by a laser beam;
3. Selective freeform deposition of material;
4. Contour cutting and adhering of sheets.

Most of the systems need some degree of post-processing to influence the quality of the finished model.

2.2 Selective hardening of photosensitive material by radiation

Basic to all systems is a photoinitiated radical polymerization process. "Polymerization is the process of linking small molecules (monomers) into larger molecules (polymers) comprised of many monomer units" [Jac92]. A loose bonding exists between small organic molecules (carbon compounds) based on Van der Waals interactions. Therefore, these molecules tend to exist in a liquid phase. If the molecules have a carbon double bonding, it can be forcibly broken by a catalyst. Such catalysts are commonly free radicals which initiate a chain reaction. Large carbon chains arise from monomers in microregions near the site of the catalysts. The Van der Waals interaction between the molecules increases with the length of the molecules and therefore the material cures in regions of polymerization.

The key to an AF is to control the locations where the polymerization happens. The material is selectively exposed by radiation (mostly UV light). The catalysts (free radicals) are formed from a photoinitiator in the resin by a photochemical process. The photoinitiator is trimmed to absorb photons with a special frequency. In consequence, if the resin is exposed to radiation with the right frequency, the fluid is immediately hardened by low energy absorption, because of the initiation of chain reactions.

The different systems on the market and under development are distinguished from one another by the illumination process and in some details of the construction. The most used procedure is hardening the resin point by point with a laser beam. This procedure is mainly called stereolithography, although different vendors use different names for their systems.

2.2.1 Stereolithography

Figure 2.2 describes the principle and construction of an SLA 250 made by 3D Systems Inc. The light source is an HeCd laser. The laser beam is focused by lenses and deflected to the surface of a vat by two rotating mirrors. A computer uses the slice information to control the mirrors (scanner). If one layer is ready, the platform is moved one layer thickness downwards. The level of the resin surface is measured by a HeNe laser using a triangulation method and adjusted accordingly. A recoating system wipes over the resin and ensures a flat surface. The laser beam scans the contours of the next slice. Then the interior of the contours is scanned line by line, like a hatch pattern. The speed of the laser beam and therefore the intensity over an area is adjusted, so the exposed area cures in a depth a little over the layer thickness to ensure good bonding to the last layer. The whole object is built by repeating this process cycle up to the last layer. At the end the platform is raised and the object removed from the platform. Because the material is not completely hardened, the object is usually cured in a UV oven.

One important characteristic is the necessity of a support structure. It makes no sense to build an object directly on the platform because this would cause problems during the removal of the object. Furthermore, the environment is liquid and overhangs would sink down after the first layer is exposed. Therefore, an additional frame has to be built to support the object.

The distance between the mirrors and the resin surface and the angle between the laser beam and the resin surface changes dependent on the angle between the beam and the perpendicular line. The beam is therefore defocused and the shape of the beam on the surface becomes an ellipse. Inaccuracy of the parts is the result. This defocusing effect is reduced with different mechanisms by the vendors.

Based on this process, there are several systems by different vendors on the market. An overview of the systems and some information of design differences is given below. Most vendors have locations or distributors in several countries, although only the headquarters are mentioned here.

3D Systems (Valencia, CA, USA) offers three AFs (SLA-190, SLA-250, SLA-500) based on the stereolithography process and is the commercial market leader in the AF industry. Over 250 machines have been sold around the world. The numbers of the SLAs describe the size of the vats in x-y direction. The SLA-250 described above is the most widely sold AF in the world. Recently, an interchangeable vat was integrated. The SLA-500 offers a greater capacity. Furthermore, the scan rates are higher than those of the SLA-250, because of the use of a more powerful Ar^+ laser. The building velocity is high but a water cooling system is necessary. The SLA-190 is the cheapest AF of 3D Systems. The light source is again an HeCd laser, but with less output power. It is smaller and slower than the SLA-250. The defocusing effect of all machines is reduced by using a long distance between mirror and resin surface in relation to the edge length of the vat. Most of the following systems are very similar in operation to the 3D Systems equipment.

Electro Optical Systems (EOS) GmbH (Planegg, Germany) product line comprises four systems based on selective hardening of photosensitive material using a laser. The use of interchangeable resin vats allows for changes between materials with different properties. All the resin wetted parts, e.g. elevator and levelling system, are changed with the vat, making it a relatively quick and straightforward operation. An Ar^+ laser is also used by the system's STEREOS 600, 400 and 300 and the size of the vat is given by the number in mm. Also, a solid state laser is tested, which has benefits in lifetime, electrical energy and cooling, and therefore in costs. The desktop machine of EOS GmbH uses an HeCd laser and is comparatively small. In comparison to other systems the laser beam of the STEREOS systems is refocused on the surface by a flat field lens, with subsequent benefits in spot size. Another feature is a special recoating system, where resin is pumped over the hardened surface.

The "Solid Object UV laser plotter (SOUP)" line of CMET, Inc. (Tokyo, Japan) offers systems in three sizes. The SOUP 600 and 850 use no rotating mirrors. The laser beam is controlled and guided by using glass fibre and an x-y plotter mechanism. The beam is therefore always perpendicular to the surface of the resin and always focused. The benefits of circular and focused beam geometry at any location of the surface are connected to disadvantages in speed, because of movements of mechanical units. SOUP 400 and 600 can be bought either with an HeCd laser or with an Ar^+ laser.

The Laser Modelling System of Fockele & Schwarze (Paderborn, Germany) is offered in different sizes up to 500 mm in one direction according to the requirements of the customer. Current systems use an Ar^+ laser, but newer models will be delivered with a solid state laser. Distinctive features are a fast recoating system based on electrostatic effects and a new precise levelling detector. The slicing is done using CAD data, which avoids inaccuracy based on STL-files with poor resolution. The apparatus is assembled in a lab-design (figure 2.3) that enables the user to integrate their own hardware and software developments. A redesign of the housing according to industrial requirements is in process.

The Solid Creation System offered by a subsidiary of Sony Corp. named Design-Model Engineering Center (Tokyo, Japan) is available in three sizes. The smallest one with 240 mm vat size uses an HeCd laser, the others an Ar^+ laser. The whole process is very similar to the SLAs. Some special features are an on-line regulation of the laser beam diameter and a variable focal length mechanism which allows the scanning of some areas in detail [Koc93].

The Soliform System was developed by DuPont, one of the main resin vendors in rapid prototyping, and sold by Teijin Seiki (Tokyo, Japan). In contrast to other systems, the slicing is done during the process, based on the CAD file. Offered are two sizes, the Soliform 300 and the Soliform 500, both using an Ar^+ laser.

Mitsui Engineering (Japan) offers its Computer Laser Active Modelling Machine (COLAMM) with a size of 300 mm. The laser beam of an HeCd laser exposes the resin from the bottom through a glass window. During the process the platform is raised layerwise from the bottom. Therefore, less support structure is necessary in comparison to other systems.

The system of Quadrax (Rhode Island, USA) is similar to 3D Systems, but uses a more powerful, visible light laser, variable beam diameter at the resin surface, and a different recoating process. The sale of the system ceased in 1992 because of legal problems.

2.2.2 Simultaneous layer curing

Two commercial systems do not use lasers to expose the resin. A strong UV lamp or a liquid crystal display (LCD) is used to produce the necessary light. Figure 2.4 describes the process of Cubital Ltd. (Raanana, Israel) Solid Ground Curing.

A thin layer of liquid is spread (a), and exposed to a UV light source through a mask (b). Each layer is thus fully cured at the intended locations by one flash. Excess liquid, which is not polymerized, is removed (c) by vacuum suction, and replaced by wax (d) to support the model during construction. Following this the layer is milled smoothly to the controlled z value. This process cycle is repeated until the parts are finished.

The masks are produced ionographically, similar to laser printers. The negative image of a slice is toned with fine black powder on a glass plate. The toner absorbs the UV light during the exposure and is removed afterwards.

Cubital offers two machines based on this principle. The SOLIDER 5600 and the SOLIDER 4600. The larger one involves a building casing of 500x500x350 mm and the smaller one, of 350 mm in each direction. A mercury lamp is used as the light source. The machine is over 4 m long and requires a more factory-like environment than the other systems. Because of the milling process the height of the z-value can be controlled accurately and very thin layers are possible. The build-time is only dependent on the height of the parts, but not on the dimensions of the parts in the x-y direction. Therefore, the economics of the process increases with the volume of the parts in comparison to their height. Cubital uses a special data front end to fill the process chamber to the maximum density. Because there is no necessity for support construction, very complex geometries with integrated moving parts are possible. A new material which is much less brittle than their original polymer was recently offered.

At the end of the process, the parts are in a block of wax, which has to be removed. An automatic dewaxing machine is offered. The wax can be removed by hot air, water or with chemicals, but it is known to be time-consuming. A disadvantage is that a lot of waste (removed resin and wax) is created during the process, although recycling is possible to a certain degree.

Light Sculpting (Milwaukee, Wisconsin, USA) has developed a further system (LSJ) to cure one layer of photosensitive resin at a time. The design is in principle the same as in stereolithography. The resin is irradiated by a lamp through a liquid crystal display mask, which is in contact with the resin. In general, high-resolution parts are possible because of the close distance and the high accurate mask. Problems caused by shielding air from the surface of the resin (air prevents polymerization at the surface of the resin and therefore causes a very thin uncured sublayer, which is useful for good adhesion to the next layer) are mentioned as solved by coating the underside of the mask with halogenated compounds. This material causes the same effects as air. The system is offered in three sizes from 152 x 152 x 228 mm to 305 mm in each direction and 559 x 559 x 610 mm.

2.2.3 Photosensitive materials

Photosensitive resin in rapid prototyping can be divided into acrylic, epoxy and vinylether resins. The critical exposure of acrylics is commonly lower compared to the others. This enables higher scan rates or lower laser power. The shrinkage of epoxy and vinylether is low. Shrinkage causes such build-defects as curl and warpage. Therefore acrylic materials have disadvantages, when highly accurate parts are necessary.

Measurements done in a European project showed that the heat deflection temperature (ISO 75) of acrylic resins is about 40° C and of epoxy materials about 75° C [Lue94]. Acrylic resins absorb less water, with a maximum of about 3 per cent, than epoxy and vinylether. If too much water is absorbed, the viscosity may increase, the curing speed may decrease significantly, and the final parts can develop a sticky surface. It is therefore important to keep a low room moisture level, if epoxies or vinylethers are used.

The choice of photosensitive materials suitable for AFs is rapidly expanding. There are materials available which are tough, stable and accurate. Others are more flexible and smooth and some are very brittle. The physical properties of the materials are constantly being improved. Nevertheless, the prototypes are only suitable for limited functional tests. In applications the parts very often serve as master patterns to produce manifolds. Typical tensile strengths range between 50 and 70 MPa. The elastic modules reach from 1,000 MPa up to 2,500 MPa. The elongations are about 6 to 20 per cent at yield, with the exception of SOMOS 2100 with 46 per cent at yield. The impact strength is mostly about 15-30 J/m. Glass transition temperatures are between 43° C and 150° C. The physical properties of many of the materials have been published [RPR1094]. Figures 2.6a-c give an overview of the properties of photosensitive resins which have been measured and summed up by IkP, Stuttgart, Germany.

2.2.4 Developments

The Olympus Optical Company, Ltd. and the University of Tokyo, Japan, have developed a machine, where a mixture of photosensitive resin and ceramic or metal powders is hardened by a laser. Subsequently, the part is heated in order to burn off the photosensitive resin before it is sintered to its final density.

Developments to build very small machines to manufacture micro parts with high accuracy is one task. Furthermore, there are a lot of activities to develop new build styles, new materials and improved details (scanners, recoating, etc.) of the machines.

2.3 Selective fusing or sintering powder by a laser beam

The process of the following systems resembles stereolithography, although the main differences are that the material is not a fluid photopolymer but a thermoplastic powder, and it is the laser heat, not the light, that causes the hardening. Therefore high-power infrared lasers are used. The parts are produced by selective melting or sintering of powder caused by a laser beam controlled by CAD data. Although the process is termed as selective laser sintering, material is actually melted together. Sintering is a process where material is fused together below its melting point. Materials with large surfaces in close contact tend to reduce the surface tension by exchanging atoms by several transport mechanisms. The reaction velocity increases with the temperature up to the melting point. The exact physical principle is not that important for the understanding of the AF, but it should be realized that the behaviour of metals and ceramics is different to plastics. Thermoplastics have bilateral electron bonding and exist in long chains. Diffusion processes which support the sintering process in metals and ceramics are not so important in thermoplastics. The sintering process is therefore slower than in metals or ceramics and the thermoplastics are almost melted by the heat.

2.3.1 Selective laser sintering

As the selective laser sintering process begins, a very thin layer of heat-fusible powder is deposited onto the part-building cylinder within the process chamber. A laser is then used to sinter only the powder that is inside a cross-section of the part. The interaction of the laser beam with the powder elevates the temperature to the point of melting, fusing the powder particles and forming a solid mass. The intensity of the laser beam is modulated to melt the powder only in areas defined by the object's design geometry. Once the laser has scanned the entire cross-section, another layer of powder is laid on top and the whole process is repeated. The part is removed from the build chamber and the loose powder falls away. SLS parts may then require some post-processing, such as sanding, depending upon the application. Compared to other processes, however, this post-processing is minimal.

DTM Corporation (Austin, USA) brought the first commercial system onto the market. The Sinterstation 2000 uses a CO_2 laser as heat source. The process chamber is heated to just below the melting point of the material used. The intensity of the laser is modulated during the scanning to define the areas of sintering. The unsintered material supports the following layers. The process continues in a nitrogen atmosphere controlled by an atmospheric control mechanism. A gas source requirement is therefore necessary. The build chamber is cylindrical with a diameter of about 380 mm and a height of about 305 mm. Contrary to figure 2.7, the powder feeding mechanism uses two cartridges, flanking the part-build cylinder. This allows a bi-directional recoating via a roller mechanism.

A great advantage over stereolithography is that theoretically every thermoplastic material could be used. But in application, the process is developed and stable only for a limited number of materials. One reason is the high sinter and melting temperatures of a lot of materials, e.g. metals and ceramics. This causes extreme requirements for the special components of the system. Furthermore, it is difficult to find the right parameters to control the process. Nevertheless, it is possible to sinter several materials up to over 90 per cent density.

The materials used in the selective laser sintering offer numerous advantages over photosensitive resins. For example, thermoplastics provide enough strength for limited functional testing. They are machinable, and can be used as masters for low-temperature tooling. Also, most materials are extremely stable after processing and are environmentally non-hazardous and non-toxic.

Because the unmelted material serves as support, parts with very complex geometry, including internal cavities and integrated moving parts (figure 2.8), are possible.

To date, DTM offers several materials for use with the Sinterstation 2000, including polycarbonate, nylon, nylon composite and investment casting wax. New developments use metal powders coated with a polymer. Indirect sintering enables the production of metallic parts. Here, metallic powders are coated with a polymer which is melted by the laser beam. The polymer acts as binder. During a subsequent debinding and sintering process, the part is compressed to its final density of up to 99 per cent. The shrinkage has to be taken into account in building the part. Instead of subsequent sintering, infiltration is also possible. The debinded porous part is immersed in metal with a lower melting point and infiltrated by capillary effects.

EOS GmbH (Planegg, Germany) offers different laser-sinter modelling systems. They use a rectangular build room which is 340 mm wide and 390 mm or 590 mm deep. The light source is likewise a CO_2 laser. The main difference to the Sinterstation 2000 is that the process chamber is not heated, which offers benefits in manufacturing time. Furthermore, another recoating system is used. Materials used are polystyrene and polyamide. Recently, a machine for direct sintering of metal (EOSINT-M) was introduced to the market. EOS uses a patented alloy, which requires no binder material or pre-heating and exhibits almost no shrinkage during the process. It is also possible to infiltrate the porous parts.

2.3.2 Materials in selective laser sintering

In general it is possible to process every thermoplastic material. For applications the choice of material is limited by several effects. If the melting temperature of the selected material is high (over 1,000° C for most metals), the processing requires a high kinetic energy. This energy has to be brought into the material. The laser power necessary for the sinter process increases with the temperature difference of the material in the process chamber and its melting point. If the chamber is heated, there is less laser power necessary. But the heating of the process chamber causes more technical requirements of the equipment and therefore increases the costs. Furthermore the heating process and the cooling after the manufacturing process needs time. If the total energy is given by the laser, there is a high local temperature gradient. Here, heat dissipation is a great problem and therefore controlling the process is difficult.

Currently, industrially used materials are polyamide, polycarbonate, polystyrene, wax, glass-filled polyamide and a metallic alloy. The wax was mostly used to manufacture master patterns for investment casting. In application, it is being replaced more and more by polycarbonate and polystyrene, because of the higher accuracy of these parts. The investment casting process of these materials is used even more in foundries. Figure 2.9 gives an overview of the properties of the different materials.

Direct sintering of metals with room temperature is currently only possible for one metallic alloy. It is foreseen that it will be difficult to expand this process to other metals, with the exception of some special alloys in the near future. The indirect sintering of metals and ceramics by use of coatings offers a lot of materials, but the total process is more complex. Debinding and final sintering processes and parameters have to be developed for every material system.

2.3.3 Developments

In different laboratories the selective laser sintering process is modified over a wide range. The following information will only give an impression of some ongoing activities.

Whereas selective laser sintering uses a powder bed, the powder could also be brought into the laser beam by a downstream technique. The pulverulent material is injected into a laser beam via a nozzle. Because the powder is in the laser beam for a long time it is melted to a higher degree than in selective laser sintering. But the complexity of the geometry and the accuracy is more limited. Developments are going on at several research facilities, e.g. the University of Stuttgart (IKP), Germany, the Fraunhofer Institut IPT and ILT in Aachen, Germany, and at the Los Alamos National Laboratory in New Mexico, USA.

Selective Laser Reaction Sintering (SLRS) was developed at the University of Texas in Austin (USA) and combines SLS with a simultaneous powder-gas-reaction. Important parts of the apparatus are:

1. A laser with modulated intensity;
2. A system to distribute powder;
3. A system to mix different gases.

The powder distribution is similar to SLS. The whole process chamber is assembled on an x-y controlled desk. The laser beam is brought into the chamber through a ZnSe window. N_2, H_2, NH_3, Ar^+, O_2, CH_4 and C_2H_2 have been tested (figure 2.10).

2.4 Selective freeform deposition of material

The main principle of the following technologies is the selective trapping of material. It should be considered that this is one of the main principles of how things originate in nature and technique. It could be realized by many physical and chemical effects. Rapid prototyping realizes the selective freeform extrusion of material. It is a principle used in an increasing number of AF systems with a lot of technical variants. All of the following technologies use a moving nozzle or jet, through which material is extruded. The developments began with fused deposition modeling, 3-D-printing and ballistic particle manufacturing.

2.4.1 Fused deposition modeling

Fused deposition modeling (FDM) was invented by Scott Crump in 1988 and is sold by Stratasys Inc., Eden Prairie, USA. The parts are built layer by layer. Liquid thermoplastic material is extruded and then deposited into thin layers. The main feature of the system is an x-y controlled heated head. The material is supplied in the form of a wire with a diameter of 1.25 mm on a spool. At the head, the wire is heated and maintained just above (1° C) the solidification point. The liquid material solidifies very quickly after it is ejected from the nozzle. By moving the head controlled in the x-y plane one layer is deposited. The diffusion breadth is between 0.22 mm and 2.5 mm, depending on the nozzle used, material feed and velocity of the head. After this, the platform is lowered one width layer and the deposition continues. The width layer ranges between 0.03 mm and 0.7 mm. It is possible to clean the nozzle automatically during the process. In brief, the process could be termed as an inverse NC milling process (figure 2.11).

Stratasys' first machine was the 3D Modeler. The size of the process chamber is 240x350x300 mm. Nowadays, it has been replaced by three machines, the FDM 1000, FDM 1500 and FDM 1600. The process chamber is reduced to 250 mm in each direction, the dimension of the total machine is very small and the term "desktop apparatus" is indeed correct. The process room of the FDM 1000 is not heated. Only the polyamide P301 is machinable with this system. The FDM 1500 integrates an engine room heating and a replaceable FDM head. Therefore all offered materials could be machined. The FDM 1600 incorporates a dual-material delivery system. The second nozzle is used to create parts of the support structure with a special wax wherever a support comes into contact with the part. Therefore, it is easy to eliminate the support structure, which is of considerable advantage when compared to other machines.

The system requires no exhaust hood or special facilities and can be used in a normal office. Offered materials are investment casting wax, machinable wax, polyolefine and polyamide. The material properties can be seen in figure 2.12.

2.4.2 ModelMaker

Sanders Prototype, Inc. (Wilton, USA) offers a similar system called ModelMaker. The MM-6B plotting system is a very small system of under 600 mm in each direction. The desktop machine is a liquid-to-solid inkjet plotter with a separate z-axis input. It uses a dual ink-jet printing system which rides on an x-y drive carriage and deposits both thermoplastic and wax materials onto the build substrate under program control. The parts are built on a platform which lowers itself by one layer width after each layer is deposited.

The build and support materials are digitally deposited onto the build substrate as a series of uniformly spaced "micro-droplets". The wax is laid down to provide a flat surface and serves as support material. The x-y drive carriage also energizes a flatbed milling subsystem to maintain precise z-axis dimensioning of the model by milling off the excess vertical height of the current build layer. The ModelMaker also has the ability to provide different specified cellular fill patterns, such as solid fill or honeycomb fill within the wall structures. After about 12 hours' operation the material has to be replenished by the operator.

The build material used is a thermoplastic material. It is said that it has good burn-out characteristics in investment casting. The support material has another colour and can be removed with a solvent. The material has a glass transition temperature of 85° C [RPR1095].

2.4.3 Ballistic particle manufacturing

Perception Systems, Inc. (Easley, SC, USA) was formed in 1988 to develop an AF system based on the patent granted to William E. Masters. The system, called ballistic particle manufacturing, deposits material in an organized pattern to build a part. The material delivery system is attached to a robotic system. The company became BPM Technology (Greenville, SC, USA) and has introduced the Personal Modeler this year based on ballistic particle manufacturing. The system uses a drop-on-demand piezoelectric jetting system to shoot microscopic particles of molten thermoplastics that solidify when hitting the part surface being built. The ejector has five-axis motion to control the droplet stream. Because of this multi-axis construction, complex geometries can be built. Furthermore, it is necessary to shoot rectangular to the surface because of the high velocity (2,540 mm/s) of the droplets. A second head follows the ejector to ensure a smooth surface. As in most AFs the part is built on a platform which is lowered after each layer. The plastic used was developed for this process and has a melting point of about 105-110° C. The final part can be sanded and drilled if necessary. Furthermore, the material is suitable for investment casting processes. The build room of the machine is 254x203x152 mm (figure 13).

2.4.4 3-D printing

3-D printing is a process developed at the Massachusetts Institute of Technology (MIT) in Boston, USA. Whereas most AF first focused on plastic parts, 3-D printing is a process developed to directly produce metallic and ceramic parts. Similar to selective laser sintering of coated powder, first a green part of a powder-binder mixture is built during the process. Figure 2.14 shows the basic steps of the principle. A roller system distributes powder spread over the surface of a bed of loose powder and the already built part. The powder is selectively joined together by deposition of a liquid binder using a process similar to ink-jet printing. After lowering the platform the process cycle is repeated until the part is complete. The unbound powder serves as support structure. After heat treatment, the unbound powder is removed. To produce ceramic parts the powder bed consists of ceramics, such as alumina or zircon. An inorganic binder (generally silica) is used as binder. Firing of the dried shell fuses the silica to form a glass bond. Metallic powder can also be glued together by deposition of a suitable binder. Then the green part has to be debinded and sintered or infiltrated.

A licence to commercialize the process for metal casting was granted to Soligen (Northridge, CA, USA). They call the process direct shell production casting (DSPC). The process is optimized to build ceramic investment casting shells for molten metals (e.g. A356 aluminium). The system focuses more on rapid tooling than on producing prototypes. Software is used to generate geometry data of a thin-walled investment casting shell and to build an STL file. The AF then builds the ceramic part as described for 3-D printing, but a multi-jet array is used. This creates advantages in speed. The following firing process lasts approximately 5 to 10 hours, depending on the wall thickness and size. The build volume of the machine is 200x300x200 mm. The DSPC parts are somewhat less accurate than those produced by stereolithography. The surface finish of the cast parts is comparable to sand-casting and the staircase effect is mentioned as being negligible in applications. Casting in aluminium, stainless steel, cobalt chromium, zinc and tin is possible.

2.4.5 Multiphase jet solidification

The Fraunhofer Institut für Produktionstechnik und Automatisierung (IPA) in Stuttgart and the Fraunhofer Institut für Angewandte Materialforschung (IFAM) in Bremen, Germany, together developed a process called Multiphase Jet Solidification. In contrast to 3-D printing, the total mixture (powder-binder-mixture) is deposited by a controlled jet.

The mixture is heated in a material chamber to a temperature within a range of 70 to 100° C, dependent on the materials used. Materials similar to powder injection moulding are used. At the temperature mentioned the mixtures have a suitable viscosity for extrusion through a jet. Because of its low surface tension the material can be deposited precisely and without contraction. Green parts are built similar to that of fused deposition modelling. Subsequently, the green parts are processed like a metal injection moulded (MIM) part by debinding and sintering to final density. The microstructure of the prototypes is comparable to an MIM part. Shrinkage has to be taken into account. Parts have been produced in stainless steel (316L).

titanium, alumina and silicon carbide. The process aims to directly produce metallic parts and ceramic tools. Trials to deposit metals with low melting points from a liquid phase have also been carried out. Recently, the first apparatus was ordered (figure 2.15).

2.5. Contour cutting and adhering of sheets

Glueing flat pieces together to create 3-D models is a method long used in art, architecture and other applications. The computer-aided automation of this process started in the early 1990s. The basic principle of such machines involves two main steps. One is to glue planar slices together. The second is to cut the shapes out of a planar piece. The most commonly used process is laminated object manufacturing.

2.5.1 Laminated object manufacturing

Helisys Inc. (Torrance, CA, USA), which was formerly Hydronetics, developed and commercialized the laminated object manufacturing process. The parent material is polyethylene-coated paper, which is available on a paper drum. The parts are, as usual, built on a lowering platform. New paper is pulled over the platform. A heated roller moves over the surface of the paper. Hereby, the polyethylene fuses and the paper is pressed and glued on the built block of paper. An x-y-controlled optic head focuses the laser beam of a CO_2 laser on the surface. The borders of the slice are cut exactly only on the top layer. After each layer, the exact z-value of the surface of the new layer is measured and the platform is lowered. Afterwards, the 3-D geometry file is sliced on the next layer and the information is downloaded to control the laser beam for the next layer. This on-line slicing process is necessary to ensure accurate building because of a variation in the layer thickness of the paper. To support the removal of the excess material once the parts have been built, the exterior of the slice is hatched. At the end the parts are included in a rectangular block. The surrounding material is cut into cubes (by the exterior hatches) and can be easily removed. But in the case of hollow details, the part has to be cut into several pieces to ensure the removal of the surrounding material and then has to be glued together afterwards (figure 2.16).

The machine is available in two sizes. The LOM-1015 has a working area of 250 x 370 x 360 mm and the larger one (LOM-2030) a working area of 560 x 810 x 510 mm. The prototypes have an uncanny resemblance to wood. One disadvantage is the tendency to absorb moisture. A new plastic material for the LOM process is expected at the beginning of 1996. The new material is predicted to be stronger than the current paper material, will absorb less moisture and will swell less. Technical values of the current material are [KPR1094]:

Elastic modules (ASTM D638):	392 N/mm^2
Braking elongation (ASTM D638):	8%
Tensile strength (ASTM D638):	34 N/mm^2
Melting temperature of the polyethylene:	94° C

2.5.2 Rapid prototyping system

A system very similar to LOM was presented by Kinergy Pte., Ltd. (Singapore). The system is available in two sizes (400x300x350 mm and 1200x900x700 mm). The cutting tool is again a CO_2 laser with a Cartesian robot to move the laser beam. The material is slightly harder than that of the Helysis system (figure 2.17).

2.5.3 Selective adhesive and hot press process

Kira Corporation Ltd. (Tomiyoshi Shinden, Japan) has also commercialized a process with the main steps being the cutting and glueing of paper. In contrast to LOM, the paper is not coated prior to the process. Resin powder, i.e. toner, is selectively printed on a piece of paper by a Xerography printer. Then the sheet is aligned on a press table. The toner faces downwards to the press table. The already built block (target block) is moved with the printed sheet to a hot plate located above them with high pressure. The toner is melted by the heat and the sheet is glued to the block. In this way, only the desired areas adhere to the block. After this, the borders of the areas are mechanically cut around. This process cycle is repeated until the object is finished. Because the paper is only selectively glued together, the surrounding material consists of loose pieces of paper, which are easier to remove than total blocks. A problem could be the control of sharp borders and having a good adhesion. The build room of the machine is 400 x 280 x 300 mm and the objects closely resemble wooden parts. The tensile strength of the composite material is claimed to be 6.5 kgf/mm^2 and the bending strength in a range from 4 to 5.5 kgf/mm^2. The material is similar to wood and can easily be polished by sandpaper.

2.5.4 LaserCAMM

A semi-automated process is LaserCAMM of Scale Models Unlimited (Menlo Park, CA, USA). The system was originally designed for architecture. Two-dimensional patterns are cut from a sheet by a high-power laser. The sheet material may be paper, wood, plastic, rubber, composites, etc. The 2-D patterns are manually assembled (glued together). It is possible to align the layers by using indexing pins and registration holes. The LaserCAMM system uses a CO_2 laser and the material thickness ranges from 0.03 mm to 25 mm.

2.5.5 Sparx AB

A further semi-automated process is Sparx AB, developed by a company with the same name from Gothenburg in Sweden. As an alternative to the above-mentioned processes, precoated (with wax paper) polystyrene films are first cut and then glued together. The borders are cut by a heating electrode instead of a laser. The cut parts are assembled and glued together by the operator and the surrounding polystyrene of the defined areas is removed manually. The rest is used to build the part by placing and assembling it in the object builder. The layers are fixed by use of preprocessed assembling holes and pressed with a hot plate. Then the wax coating is also removed and the next cycle can begin. The system is very cheap but needs a lot of manual work. Production of the system has ceased.

2.5.6 High-pressure water jet cutting

Similar to LaserCAMM, a high-pressure water jet can also be used to cut planar slices. In contrast to a laser, the water jet is more suitable for cutting stone, glass or other materials. Figure 2.18 shows parts cut by a five-axis high-pressure water jet cutting machine. All systems mentioned use one slice to create one layer, which causes the staircase effect. Some experiments at the Fraunhofer Institut für Produktionstechnik und Automatisierung were carried out to control the water jet by use of the cross-section of the top surface and the bottom surface of every slice. In this way, the top surface of a slice has the same contour as the bottom surface of the following slice. This avoids the staircase effect. To control the jet, it is necessary to have a parametric description of the contours. An automated slice algorithm for this purpose is not yet developed and requires a lot of research.

3. *Data processing for additive fabricators*

A rough description of data preparation for AFs was given in section 2.1. In detail, the process is more complex and influences the final quality of the parts. Beginning with the designed object in a special CAD system or design system, an unambiguous 3-D geometry description is necessary for the slicing process. Therefore, the result of the design process must be a solid model or a closed surface description. Using a surface description, the designer has to be more careful to trim the faces. Badly trimmed or missing faces will cause errors in manufacturing. As usual, the object is not directly sliced in the CAD system. Often data exchange to a service bureau is necessary, where the geometry is sliced and the data are prepared for the specific AF. The different file formats used in rapid prototyping can be divided into three categories.

1. Neutral exchange format for CAD;
2. Faceted formats for rapid prototyping;
3. Slice formats.

There are different possibilities in RP to exchange and convert data from the part designed in a CAD system, to the NC code for the manufacturing machine. All commercial RP systems build parts layer by layer. Therefore, all known machines use information about slices (2-D) of the part to generate NC code. The different ways of exchange and conversion are shown in figure 3.1. It has to be considered that often a support construction must be created, which is not shown in the figure.

3.1 Neutral exchange formats

Usually, the exchange of geometry data is done via neutral data models. The problems of information loss with this format are well known in CAD. Therefore, only the most commonly used models are listed, with some information about their content. It should be mentioned that the developments to STEP aim at a world-wide standard model for the exchange and storage of product relevant data. There are many activities concerning the use of STEP in RP, which are not mentioned in this article.

IGES:	(Initial Graphics Exchange Specification), USA, ANSI Y 14.26 M: 2-D/3-D line, surface and solid models (CSG), finite element methods, schemata, technical draftings
VDA-IS	(Verband der Automobilindustrie – IGES Subset), Germany, subset of IGES 3.0: Draftings, freeform surfaces
SET:	(Standard d'Echange et de Transfer), France, AFNOR-Proposal Z68-300: 2-D/3-D line, surface and solid models, process data, technical draftings
VDA-FS:	(Verband der Automobilindustrie Flächenschnittstelle), Germany, DIN V 66301: Freeform curves and surfaces, and topology
DXF:	(Data eXchange Format), format developed for AutoCAD: Draftings
STEP	(Standard for the Exchange of Product Model Data), International, ISO/TC 184/SC4/WG1: 2-D/3-D geometry models, process and manufacturing information, etc.

In rapid prototyping the above formats are mostly used only for the exchange of the geometry data between CAD systems. The faceted format is mostly computed in a CAD system, although there are software tools available to convert the above formats to STL. Even STEP to STL converters are offered. In the past, only some companies were able to develop slice tools, because the syntax of the special slice format was available only for some selected partners. Therefore, direct slice interfaces were only available between some selected CAD systems and special AFs. Because some important AF vendors published the definition and description of their slice formats, direct slice interfaces of CAD systems became even more important. Benefits will be explained later. Slicing of neutral formats is sometimes also carried out.

3.2 Faceted formats for rapid prototyping

The STL became a de facto standard for 3-D geometry data in rapid prototyping. It is a very simple format, but has greatly simplified developments in rapid prototyping. The STL file allows the representation of triangles and their normals. The triangles must represent a closed surface (solid) of the object. The normals must aim at the exterior side. There is a binary and an ASCII version of the format. A similar format was developed by Cubital Ltd. and named Cubital Facet List (CFL). It has some benefits concerning storage and syntax, but is not widely used. Most 3-D CAD systems offer STL interfaces. But no interface always produces correct STL files, although the quality is increasing. Software tools to verify and prepare STL files are on the market. Errors like wrong normals or small holes can be corrected automatically. If there are missing facets, an interactive process with the designer is necessary. To produce STL files, two parameters can be selected which influence the resolution of the triangulation process. The higher the resolution, the more triangles are produced and more storage place is necessary. The quantity and speed of processed data in the computer industry has increased greatly, so it is possible to work with much more information at the same time than some years ago. Therefore the highest possible resolution is often selected. Nevertheless, the accuracy of the AF part can be limited by this triangulation process in applications.

3.3 Slicing and slice formats

In contrast to the 3-D representation, no common standard slice format exists. Nearly every vendor uses their own slice format, e.g. SLI, SLC, CLI, HPGL. The content of these different slice formats varies from pure geometric information to machine-specific data. One benefit of HPGL data is that more geometry primitives, such as circles and arcs, are defined and most CAD systems include HPGL interfaces for drafting of cross-sections. The other formats are better fitted to the requirements of the actual AFs. Additional to HPGL, a common format for plotters, vendors of AFs started to publish their slice formats. 3D Systems published the SLC format, and the CLI format was developed in a European project and also published. Without going into the details of these formats, they were first developed to contain information necessary in stereolithography and selective laser sintering, although they are said to fit to other processes.

Slices are the lowest common denominator among RP systems. For several reasons the users' requests for a neutral slice format is increasing. The choice between different RP systems in product development enlarges. Users want to apply the same software for different RP systems as they prefer direct slice. Some benefits of a de facto slice format are:

- Software developers have free access to the syntax. The free access simplifies the development of software tools to improve data handling. For users, the choice between the different software tools would increase;
- CAD vendors are more willing to develop a slice interface if there is one common format;
- In medical applications the output of tomographs is slice information. A common direct link to nearly all RP systems would be available;
- Corrections of errors in the geometry description are easier to make in some cases;
- In developing new RP systems, there is no need to develop an individual slicer.

Admittedly, there are a lot of applications where the use of slice information has disadvantages. It is impractical to exchange geometric information for LOM, because the slice thickness varies on-line during the process. Furthermore, there are disadvantages in manipulating the part, e.g. rotating of sliced parts. But once again, it should not replace a facet format, but supplement it. The decision of which one to use for different applications is the task of the users.

A further important task in data processing is the slicing method itself. In general, direct slicing of CAD data and slicing of facet formats are the alternatives. The opinions on direct slicing and on slicing of facets break up in a wide range, dependent on experience, habits and strategic aims. From a mathematical point of view, there is no difference. Accuracy depends on the quality of the software and not on the choice. The mathematical expenditure to compute a facet format and slice it afterwards is in general equal to direct slicing. Practically, there are a lot of differences in quality, ergonomics, time and costs dependent on the available software and on the special application. The users should be able to decide themselves. In fact, the users mostly do not have the choice, because there is a lack of a de facto slice standard and consequently a lack of software tools to support direct slicing.

It is a very seldom mentioned fact that simple slicing routines involve failures which directly cause inaccurate parts. The reason is shown in figure 3.2. Subject (a) illustrates a detail of a part. During the slice process, parallel cross-sections are computed. The intersections of these parallel planes with the surface of the object result in the borders of the slices. Parts are commonly built by using the cross-section as information for the top surface of one layer. Therefore, the slice process begins one layer thickness higher than the bottom of the object. In first approximation, the object is built as shown in subject (b). It should be recognized that the object is built with oversize and undersize dependent on layer thickness and the surface orientation. Usually AF objects are surface-finished to reduce the staircase effect after fabrication Regarding subject (b), there are regions built with undersize. Surface treatment of these regions will cause more inaccuracy. For some processes like stereolithography and SLS one has to consider the overcure (subject (b)) and the energy beam profile.

New slicing tools are on the market which enable the correction of the contours dependent on application and surface treatment of the object. The magnitude and direction of the deviation can be controlled by several parameters. Three standard corrections are shown in figure 3.2. Subject (d) demonstrates a correction so that the object is built so there is no oversize at any location. The parameters should be selected to produce as shown in (e), if it is planned to smooth the surface. Subject (f) shows a correction in order to produce with highest accuracy.

Figure 3.3 shows a software tool developed at IPA offering these possibilities. A chessman (rook or castle), including a second (pawn), is presented as an STL file with low resolution. The grey regions in the slice window show one slice without correction. The presented cross-section is computed a little under the top of the front door of the rook. The black lines represent the corrected borders. The correction parameters have been selected in order to produce with a high accuracy (subject (e)). Therefore borders at the door arch have been corrected to the interior side and the border of the pawn to the exterior side.

Since correction is only possible directly after the slicing process, it cannot be done after storing the slice information in a commonly used slice format. The necessary information would be lost. Dr. André Dolenc of the University of Helsinki, Finland, initiated action to include the necessary information in exchange formats for this purpose. A slice format is used, which was predeveloped in a European project and published with the term Layer Exchange ASCII Format (LEAF). The format was enlarged and defined to fit almost all AFs and include these correction possibilities. It is not planned to share LEAF as standard. Rather, it should be considered as a (easy to change) learning aid to gain experience on how a slice format should look.

3.4 Support generation

Most AFs need support structures. One possibility is to design the support structure in the CAD system. However, this process is time-consuming and a lot of practical experience is necessary. A better alternative would be software tools to automatically create the supports. Tools are available in different qualities and contents. Both support generation based on STL files and on slice files is possible. Vendors of excellent slice software are, for example, Solid Concepts, Inc., CA, USA, and Materialize NV, Heverlee, Belgium.

4. Comparison of additive fabricators

4.1 System assessment

Studies on accuracy, system costs, maintenance costs, training duration, capacity and time were undertaken by large companies or in national and international projects. Many of the results of these studies have been published. Important benchmarks are:

1. Eastman Kodak Benchmark Study [Put92];
2. CARP Benchmark, University of Leeds [Chi94];
3. Benchmarking of RP Systems, Clemson University [Jay94];
4. Chrysler benchmark comparison [SLD94];
5. Intelligent Manufacturing Systems (IMS) - A World-wide Assessment of rapid prototyping Technologies [RPR0994].

It is not intended to list the results here. Some studies have been compared and examined [Lai95] and some comments should be given. The different studies are based on different assumptions, part geometries, measurement procedures and some terms are interpreted differently. Mostly, only linear dimensions were measured. Form tolerances, e.g. flatness, circularity, parallelism, were seldom taken into account. However, the layer based building principle of AF affects more form errors (geometric tolerances) than conventional machined or turned parts. In addition to accuracy, repeatability is an important issue and should be treated separately. This is not always done. Systematical errors, which can be corrected by soft- and hardware, have to be separated from statistical errors as well. Furthermore, one should consider that the knowledge of the operator and the condition of the actual machines reflect the quality of the parts It is usual to adjust a machine if an important benchmark is planned. The results are for that reason not necessarily typical for machines running the entire day at service bureaux.

Some build defects are characteristic for AFs. These defects are termed by curl and warpage. Unfortunately, there is only a common knowledge of the defects, but no clear definition for those terms, which could be a base for comparable measurements.

More critical are comparisons of maintenance costs, training duration and time. A lot of comparisons have been done using only one or two parts. To assess the results, one has to look critically at the actual prevailing conditions of the tests. This will explain comparisons of manufacturing time. First, it should be guaranteed that all parts have been built with the same layer thickness. The manufacturing of the support structure for special parts and AFs needs nearly as much time as the part itself. Some AFs do not need support structure at all. The time for exposing one layer is with LOM a function of the border length, with SLA and SLS a function of the area of a slice, and with SGC independent of the slice. Regarding this, the actual geometry influences to a large extent the result of the comparisons. Without insinuating a purpose, it is easy to shift the result to desired direction with some understanding of the different processes.

Nevertheless, the benchmarks are very helpful, if investments in systems are planned. But most users do not instal their own machines, they get their parts from service bureaux. For these, only time, cost, quality and the properties of the prototypes are important.

4.2 System selection

More useful than discussions on which system is the best are methods on how to find the most suitable process for the actual prototype required in the actual phase of product development in an industrial application. Methods and tools to help the staff in the product development department to select the processes will come on the market soon. The basis of these methods is to find a relationship between the processes and properties of the prototypes.

A modified version of the "House of Quality" is one method to select prototype manufacturing processes on the basis of product features. These are correlated with different technologies and the most suitable technology technologies for the specific problem to be selected. The basic steps in this procedure are:

1. First of all the relevant product features are recorded. The preferred direction of measurable features is entered as a symbol. Limit values for measurable features are also entered
2. The importance of the feature in the prototype required at the current stage of development is defined and entered in the form of a weighting.
3. The possible prototype manufacturing processes are selected. Then the evaluation matrix is filled in. In the earlier stages, the values are based on low experience. Results with subsequent use of the prototypes for decision-making must be integrated in the evaluation matrix. With this quality control loop a dynamic reference matrix adapted to the company is created with values which can be entered directly in the appropriate RP Process Selection House. It is important to consider limit requirements (KO criterion).
4. The evaluations in the matrix are multiplied by the feature-weighting and the individual values for each process are added.
5. As a further refinement the limiting conditions are entered. These include anticipated costs and time until the prototype is available. By marking the processes to which the user would give priority on the basis of his experience, empirical knowledge can also be incorporated into the evaluation.
6. In the roof of the house the product features are examined in pairs to determine their influence on each other (negative, neutral, positive). In this way it is possible to identify where small modifications in the process selection might have a major impact on the prototype quality (figure 4.1).
7. Once the house has been filled, the optimum solution can be sought. However, the possibility of combining prototypes made in different ways to achieve the same quality features should also be considered.

Like the "House of Quality" extra rooms can be added to this house as well. One example is casting processes to improve the prototype quality. Through adaptation of the house to the specific products in a company and its use for product planning, the optimum technologies for manufacturing of prototypes and the most suitable suppliers can be chosen. By avoiding the manufacturing of expensive prototypes, which provide little information, costs can be reduced and the product development time can be shortened.

5. Using rapid prototyping for manifolds

As mentioned, the choice of materials applicable by AF is limited. Although new and better materials are under development, there is a great need for materials similar or equal to those used in mass-production of the actual product. To achieve these aims, AF parts are used as master patterns for pouring techniques. Dependent on the material, geometry, required quality and number of manifolds, several pouring techniques, e.g. vacuum casting, sand casting, centrifugal casting, metal spraying process, plaster moulding and investment casting are used. The general principles of these techniques are well known. For most processes it is insignificant whether the master pattern was built with an AF technology or not. To give an impression, figure 5.1 shows a general process cycle of manual vacuum casting. First, the AF master pattern is fixed in a box. Then the box is half filled with plasticine. After the plasticine is solidified the rest of the box is filled from the top with silicon (b). By turning the box, removing the plasticine and a further casting of silicon, a mould surrounds the AF part. After that, the silicon has to be cut in two or more pieces. Runner and riser outgate are drilled and the mould is finished. A silicon mould can be used for casting in a wide range of different plastics up to 30-40 manifolds depending on the geometry of the pattern. To avoid air bubbles, the process is done under vacuum. Cast resins are available as one or more component systems in all colours and a wide range of physical properties. The notations of the materials are given by the vendors and are mostly meaningless. Product overviews with physical properties, e.g. colour pot life, hardness, etc., are published by most vendors. Service bureaux generally specialize in a number of materials. Due to the materials' properties, the use of manifolds for functional testing is less limited than with AF parts. Furthermore, there is often a need for more than one prototype.

Moulds produced by metal spraying allow the casting of up to 1,000 manifolds. The patterns are first metallic coated by use of a metal spraying pistol and then backfilled. After removing the pattern a mould with a metallic coating exists. The process is expensive and more limited in geometry than vacuum casting. The elasticity of the vacuum casting moulds enables the handling of undercuts.

Other casting technologies are often used for metallic manifolds. With the exception of investment casting, the technical process need not be changed for rapid prototyping. More work has been, and still has to be done to fit the course of the casting process into the requirements of rapid prototyping. Organization and logistic optimizations were necessary to satisfy the request for fast prototypes.

For investment casting, both AF vendors and foundries had to change or improve their processes. Traditionally, wax patterns made by injection moulding are used for investment casting. As some AFs are able to produce wax parts, they can be used directly for investment casting. Unfortunately, wax is difficult to process with AF and the accuracy is not as good as that of other materials. Therefore, conventional investment casting must be modified to suit AF patterns. The effort of this modification depends on the thermal properties of the materials. Thermoplastics can be melted out of the ceramic shells by heating. Different waxes, polycarbonates and polyolefine AF parts have been used successfully. Foundries have learned to handle these materials. Other materials are not well suited for investment casting. Photosensitive resins, used in stereolithography, have to be burned out of the shell by high furnace temperatures. Further problems are a high ash content and the possibility that the parts crack the shell, caused by the positive expansion coefficient. New building styles for stereolithography have been developed to solve these problems. The process is controlled in such a way that the prototypes are mostly hollow. The internal structure is made up by a lattice construction to ensure a stable part. Nevertheless, this construction allows the part to collapse into itself rather than expand outward and crack the casting shell. One problem is to drain all the uncured material out of the part after removing the vat part. Undrained material may damage the investment casting shell. The constructions of the interior lattice are even more optimized. The experience of foundries in burning out this material is increasing.

The disadvantage of this technique is the necessity for a prototype for each manifold. The build-time and costs of the AF parts are almost linear to the number of prototypes. Direct pattern creation is certainly the fastest and cheapest way to create a single investment pattern.

Investment casting using traditional wax patterns yields successful parts for only about 85 per cent of the time. The success rate using AF patterns is lower. The number of foundries with experience in AF patterns is still low and only a few have experience with patterns of all technologies. Since most foundries are specialized in casting only certain metals, it is difficult to find one for the right combination of material and AF technology. A good alternative is the use of AF prototypes to produce dies for the manufacture of conventional wax patterns. It has been found that this process with one further step is cheaper and faster if more than three to five patterns are necessary [Mul95]. Materials used for the dies are silicon rubber, epoxy or spray metal, depending on quality, time and costs.

When using AF parts as a master for casting processes, shrinkage has to be taken into account. The AF master patterns have to be scaled. It is important that shrinkage is not homogeneous. Therefore, different areas of the parts require different scaling. Software tools to compute and simulate shrinkage are on market. In application, the special knowledge of foundries on materials behaviour is often the key to achieving good manifolds.

6. Rapid product development

The integration of AFs and casting technologies in industrial production processes plays a dominant role in the success of these techniques. Consideration must be given to the system costs, speed, materials available and accuracy. The success and acceptance of rapid prototyping systems depends mainly on an optimized integration of AF systems into existing production processes. Because of the limited possibilities of actual AF parts and manifolds, these technologies can only be one—although important—part, among conventional techniques in a process cycle for the rapid development of products. Figure 6.1 gives an overview of the steps used in rapid product development. These illustrated technologies and techniques are part of fast loops, where product specification and modification, prototyping and evaluation have to be organized in fast iterations, a simultaneous and successive sequence of processes with optimized logistic.

In this process cycle an automatic data exchange between different systems (e.g. design system, computer tomography, CAD/CAM) is important. In particular, the application of methods for quality assurance is of great significance. In industry a large number of different systems are installed with varying degrees of automation depending on size, assortment of products and organization. Therefore an information network with less redundant data between the different systems should be implemented.

In addition to these technologies, new methods of organization, cooperation and teamwork are being tested in industry and developed at research institutes. However, the use of innovative technologies certainly does not guarantee the rapid development of innovative products. The decisive factor is the flexible use of a wide variety of technologies adapted to the current situation in product development. In the following, some technologies and techniques with increasing significance for product development are listed and commented on, in order to amplify previous information. It should be considered that CAD, design systems and virtual reality are tools for product specification as well as tools to generate virtual prototypes for presentation, advertising and simulation.

Computer Aided Design (CAD)

The number and quality of tools included in CAD is steadily increasing. Small and medium-sized companies are using more 3-D CAD systems. Although the possibilities of representing 3-D geometries increase, the bulk of the efforts are to improve presentation techniques, such as rendering and animation and the integration of tools for manufacturing or simulation.

Design systems

The design of CAD systems is geared to the notations and methods of engineers, although the methods of industrial engineers often differ. Design systems have therefore been developed to offer computer tools suited to industrial designers. They offer more freedom for creativity and are commonly based on sketches. The design systems on the market offer improved possibilities to visualize transparency, reflections, shadows and textures. Tools included for animation are used even more for advertising in early phases of product development.

Virtual reality

With increasing performance of computers, virtual reality can be used more and more to represent products and shapes. It enables realistic representation and the handling of large, complex products. Leading institutes and service bureaux offer realistic simulations of products based on 3-D CAD data.

Computer tomography

Computer tomography is a widespread tool in medicine. In rapid prototyping it is used more and more to determine anatomy and generate 3-D models of bone structures.

Reverse engineering

Tactile or optical 3-D digitizing is a tool to obtain geometric data of the surface of an object. More or less automated software is on the market to compute CAD data from the measured points.

7. Business situation

The primary aim of introducing rapid prototyping technologies is to improve product development. Investments are made when new technologies offer possibilities to reduce the lead-time to market, to improve quality and save money. One problem of AFs is their high level of innovation. If a new milling comes onto the market which is twice as fast as the one used before, it is easy to compute amortization time. The decision for investment can be done on an exact calculation. The risk and responsibility of the decision maker is comparatively low. The risk in taking a decision to invest in innovative technologies is higher when less experience with comparable technologies exists. At the beginning of rapid prototyping a lot of arguments for these techniques were published which seemed logical and promising. Nevertheless, investment was only seldom done, because no experience and calculation of amortization was available. In the meantime, some companies (mostly automotive) published information about estimations of time-saving and costs with rapid prototyping. The often-heard question "Are there real benefits in using rapid prototyping?" changed to questions such as:

- Is rapid prototyping suitable for our products?
- What AF and casting technologies fit into our product line and our product development?
- Is it better to invest into own machines or should I use service bureaux?
- What should be considered if we want to use rapid prototyping?
- What is the fastest way to produce prototypes with similar properties to the final product?
- What is the fastest way to produce tools?

As mentioned at the beginning of this article, rapid prototyping changed in just a few years from first laboratory systems to widely used technologies. Nevertheless, the use is no guarantee for a successful product development. The situation is well described with the following formula:

Rapid prototyping can deliver tremendous benefits for a lot of products, but only if the overall business plan is good.

More and more companies understand the benefits and limits of rapid prototyping. The number of service bureaux is rapidly increasing and existing service bureaux have expanded their operations. Figure 7.1 gives an overview of the sales of machines. Wohlers [Woh95] estimates that the revenue from product sales and services grew by about 100 per cent in 1994, making rapid prototyping an estimated $198 million industry.

About 80 per cent of the sales have been made by USA system manufacturers. Japan follows (about 13 per cent) and then Europe. Most system developments are done in the USA. The vendors first satisfy the market in their own country before expanding to other countries. Because of this situation, most new systems and improvements are on the market in the USA first. Applications in rapid prototyping came to Europe with a delay of six months to a year. Benefits in product development through early access to new technologies are enormous and it would be daring to estimate how a time lead in rapid prototyping applications influences international competition. But looking at the present global markets, and the associated competition, one should not ignore this effect. In product development especially, a technology lead can decide who is able to offer new, high-quality products first on the market, and who will have the highest share of the profit.

This contention is supported by the fact that a lot of European companies obtain their prototypes from service bureaux in the US. Furthermore, the patent situation is of interest because it can be considered as an indicator for development activities. The patent law and the period of time until a patent application is published is different in different countries. Nevertheless, a comparison between the number of published patent applications and machines sold by some stereolithography vendors (figure 7.2) is of interest.

Over 80 per cent of the patents are US patents. To assess this data it should be considered that the average time between patent application and patent specification is 2.5 years in the USA and 4.5 years in Germany, and often longer in the rest of Europe. Some US patents are in the assessment phase in Europe. In a patent research at IPA [Gal94], 329 patent applications were found. Of these, 146 applications came from the USA, 97 from Japan, 67 from the EC and 19 from Israel.

8. Sources for further information

Useful tools for obtaining further information are books, the World Wide Web and international events on rapid prototyping. Proceedings of the following events are good, but time-consuming, sources. They give an excellent overview on activities going on in research institutes and in industry. A very fast and cheap way is the use of the Internet. In addition, there are some books listed below which give a good overview on rapid prototyping and often served as a source for this article.

International events

International Conference on Rapid Prototyping
Contact: Theresa Bohlander, Program Administrator, Management Development Center, University of Dayton, 20 Anderson Hall, 300 College Park, Dayton, Ohio 45469, USA

Asia/Pacific Conference on Rapid Product Development
Contact: Maria Richmond, Conference Officer, Queensland Manufacturing Institute, P.O. Box 4012, Eight Mile Plains, Queensland, 4113 Australia

Rapid Prototyping in Medicine and Computer Assisted Surgery
Contact: Prof. Willi Kalendar, University of Erlangen-Nürnberg, Institute for Medical Physics, Krankenhausstrasse 12, D-91954 Erlangen, Germany

Solid Freeform Fabrication (SFF) Symposium
Contact: Harris L. Marcus, Mechanical Engineering Department, University of Texas at Austin, Austin, Texas 87712-1063, USA

European Conference on Rapid Prototyping and Manufacturing
Contact: Donna Borrill, Department of Manufacturing Engineering and Operations Management, University of Nottingham, University Park, Nottingham NG7 2RD, UK

International Conference on Rapid Product Development
Contact: Dr. Wilhelm Steg[illegible], Fraunhofer Institut für Produktionstechnik und Automatisierung (IPA), Nobelstrasse 12, 70569 Stuttgart, Germany

Fundamentals of Rapid Prototyping and Applications in Manufacturing, and
SME Rapid Prototyping and Manufacturing
Contact: Lorie Hastie, Society of Manufacturing Engineers, One SME Drive, P.O. Box 930, Dearborn, Michigan 48121-0930, USA

Rapid Prototyping in Medicine
Contact: Roger Hirons, Center for Continuing Education, College of Engineering and Applied Science, University of Wisconsin, 929 North Sixth Street, Milwaukee, Wisconsin 53203, USA

PATT-TECH
Contact: DANSEI International, Inc., Fukide Building, Number 2, 4-1-21 Toranomon, Minato-ku, Tokyo 105, Japan

Scandinavian Rapid Prototyping Conference
Contact: Erika Jablanovec, IVF, Argongatan 30, S-431 53 Molndal, Sweden

World Wide Web

The World Wide Web (WWW) is an international network of computers based on the Internet. In the past the Internet was mainly used by scientists, but recently more and more companies have access to WWW. A great number of universities are connected by this network. It contains an increasing number of documents on rapid prototyping. The different documents are often linked by hypertext. This allows one to find documents easily without knowing the exact address of the host. It is only necessary to know a few hosts and an endless research can be started by only clicking on highlighted words or phrases. The system links itself to the special host address, where the linked document is stored. It is only necessary to wait some minutes if the linked host is on the other side of the world. If there is no direct access to WWW, different companies offer services, however not free of charge. Some important addresses at universities are:

http://www.eng.clemson.edu/dmg/iderp/iderp1.html—Clemson University Product Realization Laboratory
http://www.cranfield.ac.uk/aero/rapid/rapid_prot.html—Cranfield University
http://www.sffoffice.me.utexas.edu—University of Texas at Austin
http://web.mit.edu/afs/athena/org/t/tdp/www/home.html—Massachusetts Institute of Technology
http://www.udri.udayton.edu—University of Dayton
http://atlas.edrc.cmu.edu:9999/acorn/acorn_prototyping.html—Carnegie Mellon University
http://www.arc.ab.ca—Alberta Research Council
http://www.cs.hut.fi/~ado/rp/rp.html—Helsinki University of Technology
http://www.cadcam.kth.se/public/computer/fff/RP.html—Swedish Institute of Production Engineering Research

Books

Automated Fabrication—Improving Productivity in Manufacturing, Marshall Burns, Ennex Fabrication Technologies, PTR Rentice Hall, Englewood Cliffs, New Jersey 07632, 1993, ISBN 0-13-119462-3

Rapid Prototyping and Manufacturing—Fundamentals of Stereolithography, Paul Jacobs, Society of Manufacturing Engineers, Dearborn, Michigan, 1992

Layer Manufacturing—A Challenge of the Future, The final report from the NOR-SLA project, 1992, Trondheim, Norway, ISBN 82-519-1125-7

Software Tools for Rapid Prototyping Technologies in Manufacturing, André Dolenc, Acta Polytechnica Scandinavica, Mathematics and Computer Science Series No. 62, Helsinki, 1993, ISBN 951-666-393-1

Solid Freeform Manufacturing, Kochan, D., Elsevier Science Publisher e.V., 1993 ISBN 0 444 89652 X

Rapid Prototyping Systems: Fast Track to Product Realization, Customer Service Department, Society of Manufacturing Engineers, One SME Drive, P.O. Box 6028, Dearborn, Michigan 48121

Principles of Computer Automated Fabrication, Jerome L. Johnson, Palatino Press, Inc. 1994, ISBN 0-9618005-3-4

Rapid prototyping magazines

Rapid Prototyping Report, CAD/CAM Publishing, Inc.
1010 Turquoise Street, Suite 320, San Diego,
California, 92109-1159, USA

Rapid Prototyping Journal, MCB University Press
Limited, 60/62 Toller Lane, Bradford, West Yorkshire,
England BD8 9BY

EARP-Newsletter, European Action on Rapid Prototyping, Bent Mieritz, Danish Technological Institute, Teknologiparken, 8000 Aarhus C, Aarhus, Denmark

Rapid News, c/o EPC, 46 Watergate Street, Chester,
CH1 2LA, United Kingdom

References

Mul95 Investment Casting Notes. In: Rapid Prototyping Report, Vol. 5, No. 8, August 1995, pp. 3-5, CAD/CAM Publishing, Inc

Koc93 Kochan, D.: Solid Freeform Manufacturing. Elsevier Science Publisher e.V., ISBN: 0 444 89652 X, 1993

RPR1094 Material Comparison. In: Rapid Prototyping Report, Vol. 4, No. 10, October 1994, pp. 3-6, CAD/CAM Publishing, Inc.

Put92 Van Putte, D. A.: A Brief Benchmarking Study of Rapid Prototyping Processes. In: Proceedings of the 3rd International Conference on Rapid Prototyping, Dayton, OH, June 1992, pp. 251-263

Chi94 Childs, T. H. C.: Manufacturing Requirements and Performance of Layer Manufacturing Machines. D700 Final Report. CARP 94 U 0100 t

Jay94 Jayaram, D. and Bagchi, A.: Benchmarking of Rapid Prototyping Systems. Thesis, Clemson University, December 1994

SLD94 Schmidt, L. D.: A Comparison of Commercial Techniques in Rapid Prototyping. In: Proceedings of the IMS International Conference on Rapid Product Development, Stuttgart, Germany, 31 January - 2 February 1994, pp. 51-66

RPR0994 System Comparison. Intelligent Manufacturing Systems—Rapid Prototyping Test Case. In: Rapid Prototyping Report, Vol. 4, No. 9, September 1994, pp. 4-7, CAD/CAM Publishing, Inc.

Lai95 Laible, U.: Dimensional Control and Evaluation of Rapid Prototyping Processes. Diplomarbeit presented to the Graduate School of Clemson University and University Stuttgart, June 1995

Gal94 Gallasch, A.: Untersuchungen zum Verlauf der Patentsituation bei generativen Fertigungsverfahren und Analyse der Patentansprüche bei ausgewählten Verfahren. Diplomarbeit an der Universität Stuttgart, Institut für Industrielle Fertigung und Fabrikbetrieb, 1994

Jac92 Jacobs, P.: Rapid Prototyping and Manufacturing Fundamentals of Stereolithography. Society of Manufacturing Engineers, Dearborn, Michigan, 1992

Lue94 Lück, T., Baumann, F., Keller, B. and Wiedemann, B.: Material Research and Development for Rapid Prototyping Techniques at the IKP. In: Proceedings of the 3rd European Conference on Rapid Prototyping and Manufacturing, Nottingham, 1994, pp. 309-325

Figure 2.1

Common procedure in using AFs

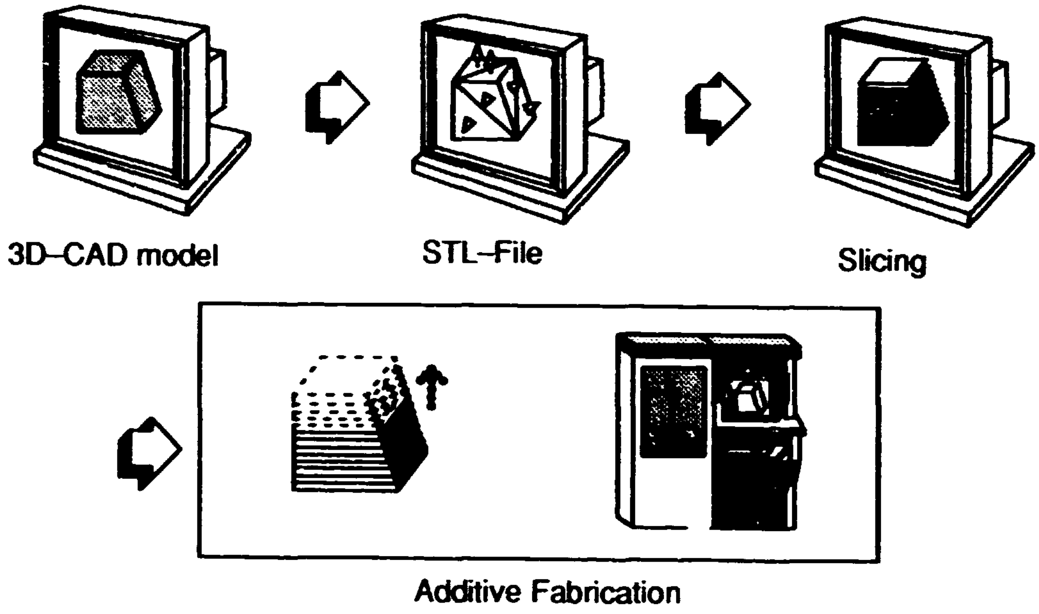


Figure 2.2

Basic principle of the stereolithography process of 3D Systems Inc.

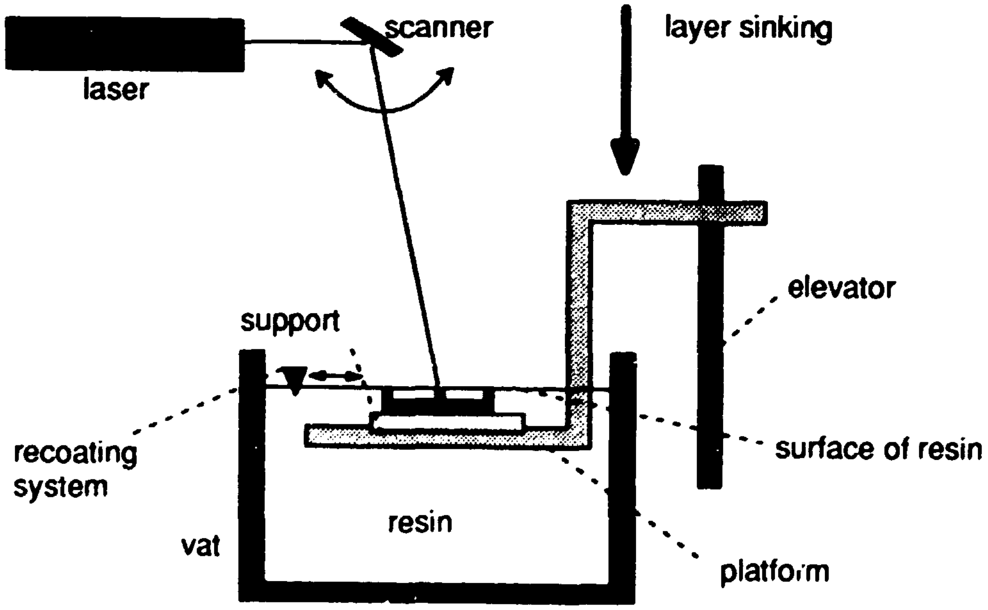


Figure 2.3

Laser modelling system of Fockele & Schwarze Stereolithographietechnik GmbH

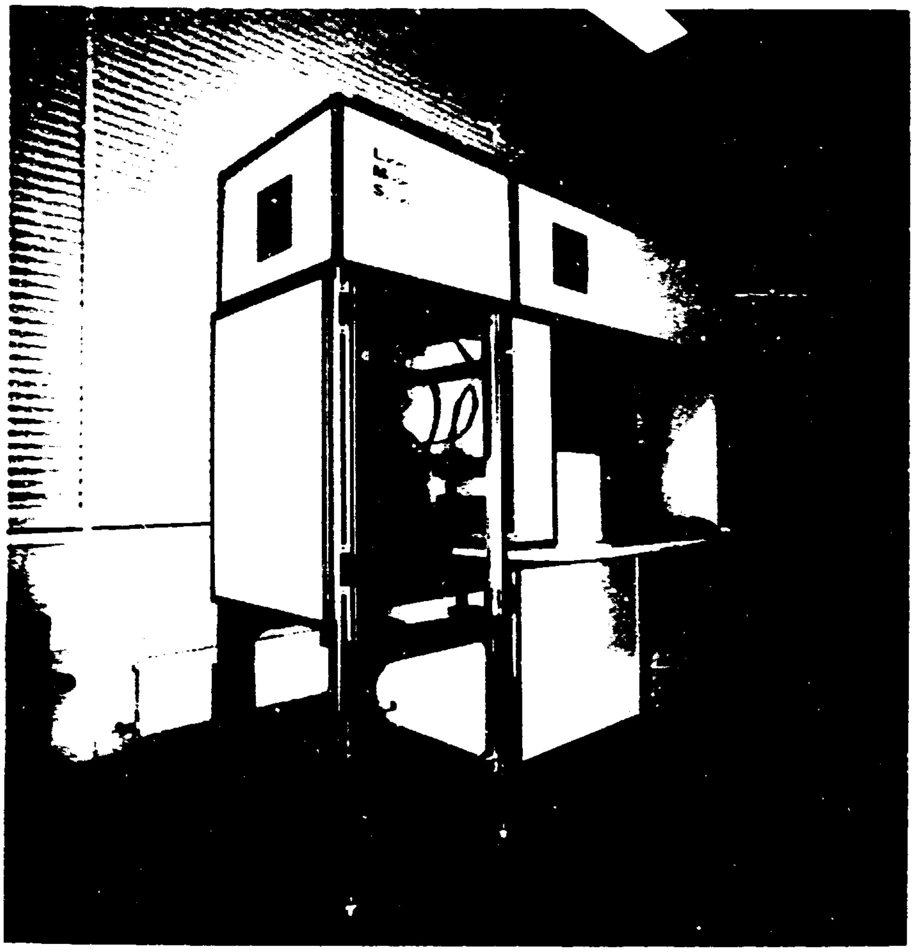


Figure 2.4

Basic principle of solid ground curing

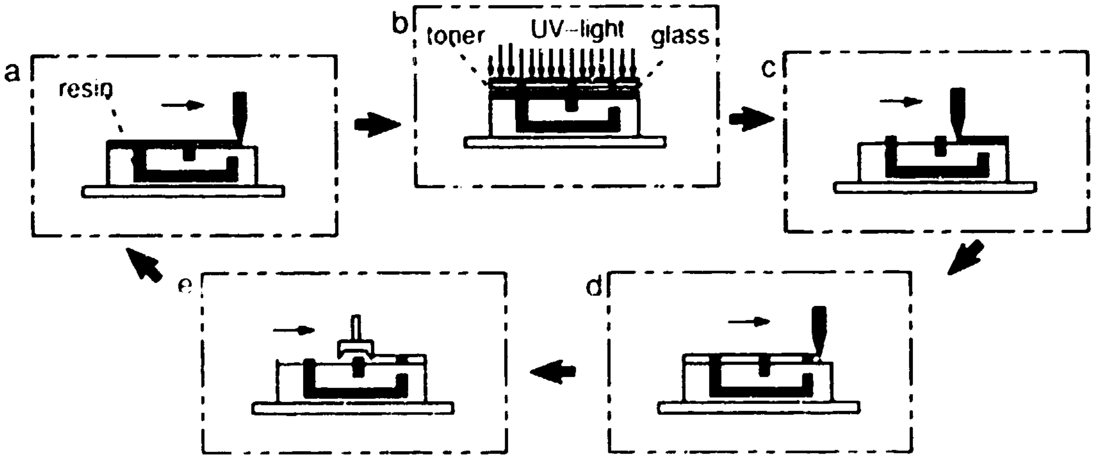


Figure 2.5

Parts made by stereolithography
(Source: Allied Signal)

Figure 2.6a

Properties of photopolymers

Vendor			Coates BR PLC	DSM Desotech	
Notation			Sol.G-5601*	D.950-805	D.4112-143*
Material				Acrylic	
Laser				Ar^+ HeCd	
A. Mechanical properties		Test			
Elastic modules	(N/mm^2)	ASTM D638	1200	1100	1000
Braking elongation	(%)	ASTM D638	12	7	18
Tensile strength	(N/mm^2)	ASTM D638	38	62	36
Notched-bar impact strength (Izod)	(kJ/m^2)	ISO 180	2		
B. Thermal properties					
Glass transition temperature	(°C)		40		100
C. Process properties					
Viscosity	(mPas)	30 °C		200-400	
Penetration depth	(mm)			0.17	
Critical exposure	(mJ/cm^2)			5.8	
Dangerous materials					NVP

Source: IKP

* Solid ground curing

Figure 2.6b

Properties of photopolymers

Properties of materials used in AF

Vendor		Ciba-Geigy						
Notation		SL 5081-1	SL 5131	SL 5149	SL 5154	SL 5177	SL 5170	SL 5180
Material		Acrylic	Acrylic	Acrylic	Acrylic	Acrylic	Epoxy	Epoxy
Laser		HeCd	Ar⁺	HeCd	Ar⁺	HeCd	HeCd	Ar⁺
A. Mechanical properties	Test							
Elastic modules (N/mm^2)	ISO R527	3000±500	3000±500	1100	1100	1105±35	2450±50	2500±100
Braking elongation (%)	ISO R527	2.5±0.5		10±2	15±4	12.5±2.5*	13±6	10±1
Tensile strength (N/mm^2)	ISO R527	62±11	70±10	35	35	30	60	60±5
Notched-bar impact strength (Izod) (kJ/m^2)	ISO 180	3±1	3	22.5±2.5	22.5±2.5	28±1	28.5±1.5	37±10
Hardness	Shore D	87-91	87-91	78	78	78	85	84
B. Thermal properties								
Glass transition temperature (°C)		150	150	~83	~83	72	65-90	60-85
Thermal stability (°C)				42			49	42
Coefficient of thermal expansion (1/°C)		81**						52/172***
C. Process properties								
Viscosity (mPas)	30° C	2400±800		2000±400	2000±400	2000±400	180±15	187
	35° C	1150±200	1280±200					
Penetration depth (mm)		0.19	0.18	0.15	0.13	0.27	0.12	0.13
Critical exposure (mJ/cm^2)		6.6	5.0	6.1	4.2	11.2	13.5	16.2
Dangerous materials		NVP	NVP		/	/	/	/

The values are partly given by the vendors and partly measured at the Institut für Kunststoffprüfung und Kunststoffkunde (IKP) of the University of Stuttgart, Germany.

Source: IKP.

* ASTM D638.
** 40° C - 100° C.
*** -100° C - 50° C/50° C - 200° C

Figure 2.6c

Properties of photopolymers

Properties of materials used in AF

Vendor		Du Pont				Allied Signal		
Notation (S→SOMOS/E→Exactomer)		S2100/ 2110	S3100/ 3110	S5100/ 5110	S6100	E2201	E2202 SF	E5201
Material		Acrylic	Acrylic	mod. Acrylic	Epoxy	Vinylether	Vinylether	Vinylether
Laser		Ar^+/HeCd	Ar^+/HeCd	Ar^+/HeCd	Ar^+	HeCd	HeCd	Ar^+
A. Mechanical properties	Test							
Elastic modules (N/mm^2)	ASTM D638	37	810	875	2690	1455±276	1750±250	1380
Braking elongation (%)	ASTM D638	46	9.2	10	7.1-11.4	8±2	7±1	6.5±0.5
Tensile strength (N/mm^2)	ASTM D638	7	21	22	54	55±7	68±7	48
Notched-bar impact strength (Izod) (kJ/m^2)	ISO 180	150	15	14	34	21.5±0.3	32±3	30-43
Hardness	Shore D	41	80	97	84.5	80	80	84
B. Thermal properties								
Glass transition temperature (°C)		~43	~43	~60	~53	65	~75	84±6
Thermal stability (°C)	ASTM D648				49	46.5±0.9	46.5±0.9	48
Coefficient of thermal expansion (1/°C)		150-180	150-200		49/174***	47.5/243**	47.5/243**	52/175***
C. Process properties								
Viscosity (mPas)	30° C	3805±285	985±15	6000	265	205	230	240 (32°C)
	35° C							
Penetration depth (mm)		0.22/0.12	0.19/0.13	0.22/0.12	0.12/0.17/ 0.15*	0.18	0.17	0.18
Critical exposure (mJ/cm^2)		2.9/3.5	4.0/2.4	9.9/2.8	12.2/25.9/ 26.8*	27±5	8.5±1.7	15.2
Dangerous materials		/	/	/	/	/	/	/

The values are partly given by the vendors and partly measured at the Institut für Kunststoffprüfung und Kunststoffkunde (IKP) of the University of Stuttgart, Germany.

Source: IKP.

* 351 nm/351+364 nm/333+351+364 nm

** 0° C - 60° C/60° C - 155° C.

*** -100° C - 50° C/50° C - 200° C

Figure 2.7

Principle of selective laser sintering

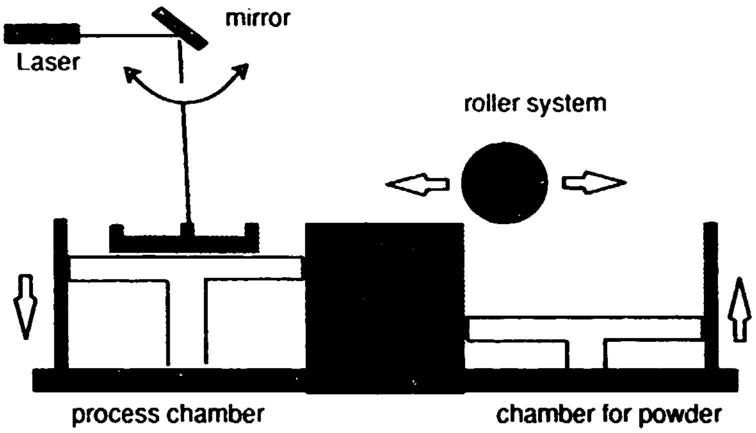


Figure 2.8

Parts made with selective laser sintering (SINTERSTATION 2000)

Figure 2.9

Properties of sinter materials

Properties of materials used in AF

Vendor		B. F. Goodrich					EOS GmbH	
Notation		LPC-30000	LN-4010	LNF-5000	LNC-7000	LWX-2010	PS 1500	PA 1500
Material		Polycarb.	Polyamide	Polyamide	Composite	Wax	Polystyrene	Polyamide
Laser		CO_2	CO_2	CO_2	CO_2	CO_2	CO_2	CO_2
A. Mechanical properties	Test							
Elastic modules (N/mm^2)	ASTM D638	1220	1400	1400				1090
Braking elongation (%)	ASTM D638	5	24	24	5			)15
Tensile strength (N/mm^2)	ASTM D638	23	36	36	42			35-40
Notched-bar impact strength (Izod) (kJ/m^2)	ISO 180	53	70	70	68			
Hardness	Shore D							
B. Thermal properties								
Glass transition temperature (°C)		150				63	110	85
Melting point (°C)			186	186				
Heat resistance (°C)			163	163	188			
C. Process properties								
Grain particle size (μm)			120	50	50/35		80	
Dangerous materials		/	/	/	/	/	/	/

The values are partly given by the vendors and partly measured at the Institut für Kunststoffprüfung und Kunststoffkunde (IKP) of the University of Stuttgart, Germany.

Source: IKP.

Figure 2.10

Selective laser reaction sintering

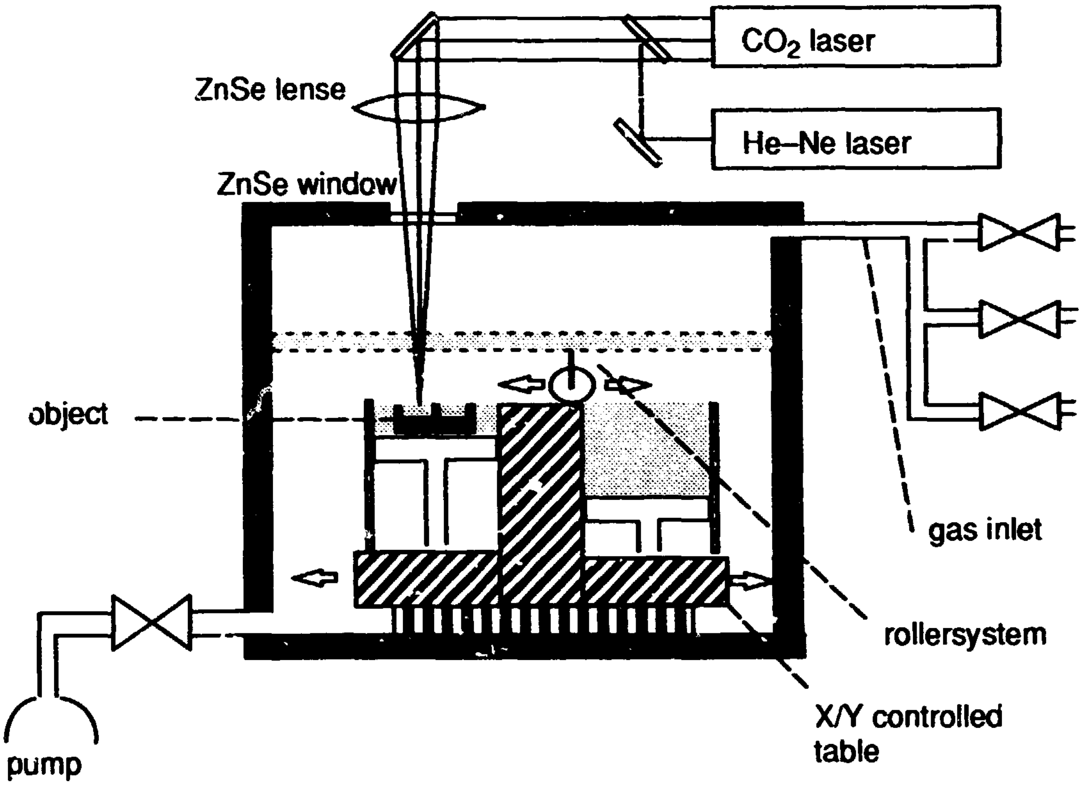


Figure 2.11

Working principle of fused deposition modeling

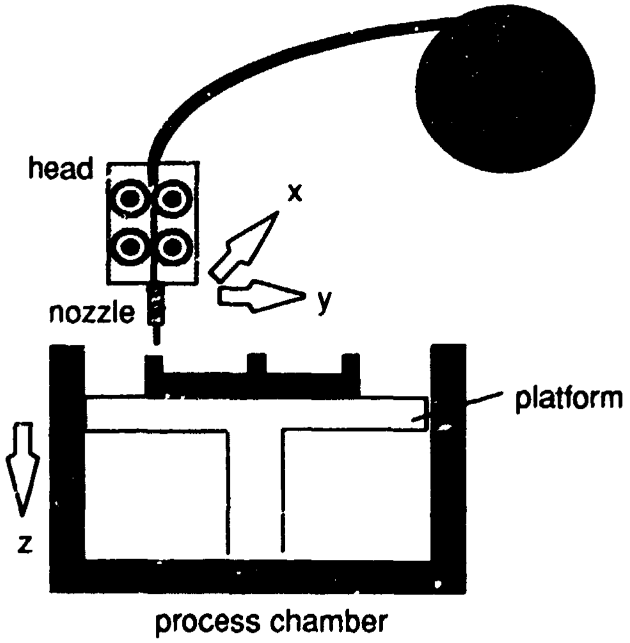


Figure 2.12

Properties of materials for fused deposition modeling

Vendor			Stratasys	
Notation			Plastic 200	Plastic 301
Material			Polyolefine	Polyamide
A. Mechanical properties		Test		
Elastic modules	(N/mm^2)	ASTM D638	630	560
Braking elongation	(%)	ASTM D638	4.7	3.5
Tensile strength	(N/mm^2)	ASTM D638	10	12
Notched-bar impact strength (Izod)	(kJ/m^2)	ISO 180	9	13
Hardness		Shore D	58	70
B. Thermal properties				
Melting temperature	(°C)		72-108	100-110

Notation			ABS P400	Casting wax
Material			ABS	Wax
A. Mechanical properties		Test		
Elastic modules	(N/mm^2)	ASTM D638	2600	281
Braking elongation	(%)	ASTM D638	50	3.5
Tensile strength	(N/mm^2)	ASTM D638	34	3.6
Notched-bar impact strength (Izod)	(kJ/m^2)	ISO 180	106	13
Hardness		Shore D	105 (Rockwell)	33

Source: IKP.

Figure 2.13

Working principle of ballistic particle manufacturing

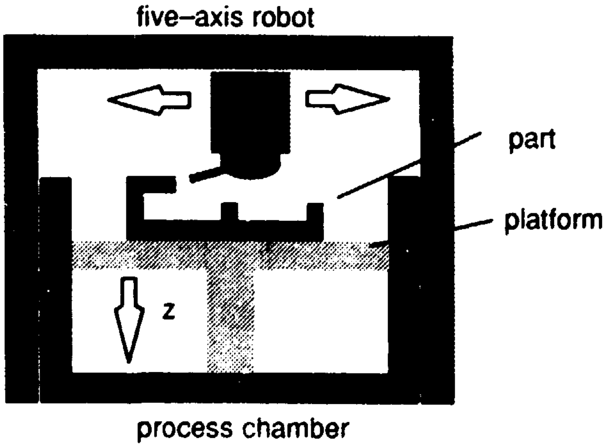


Figure 2.14

The direct shell production casting process cycle

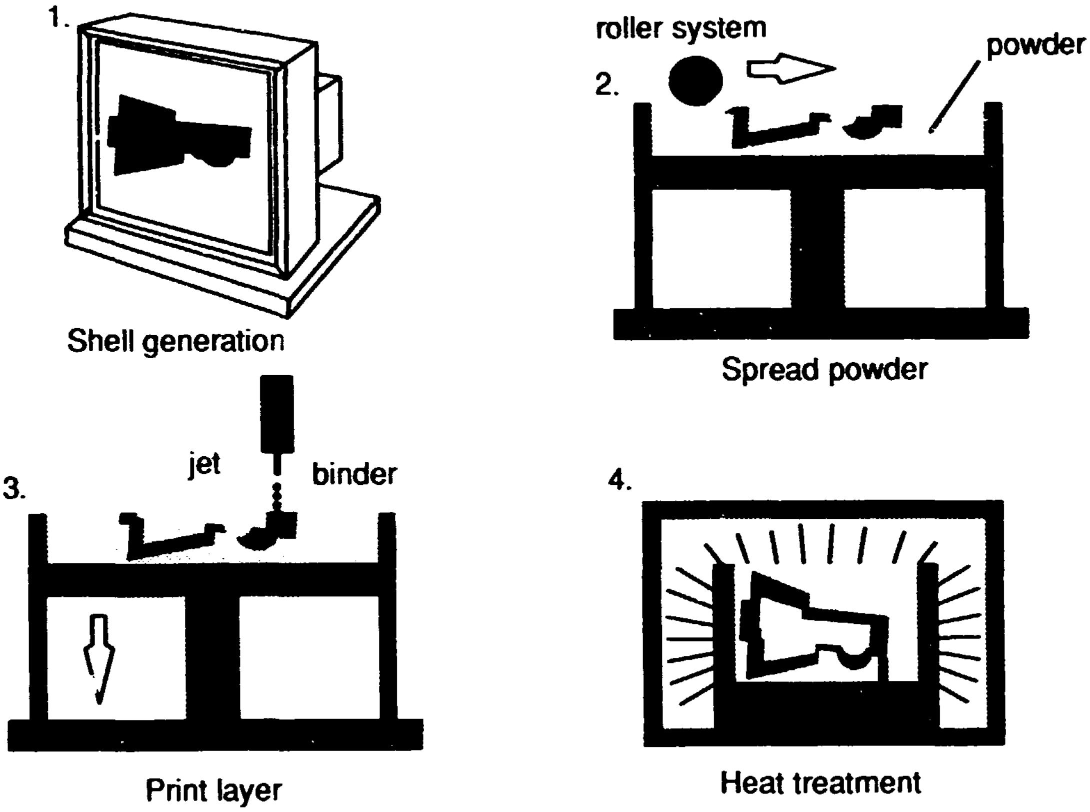


Figure 2.15

Multiphase jet solidification

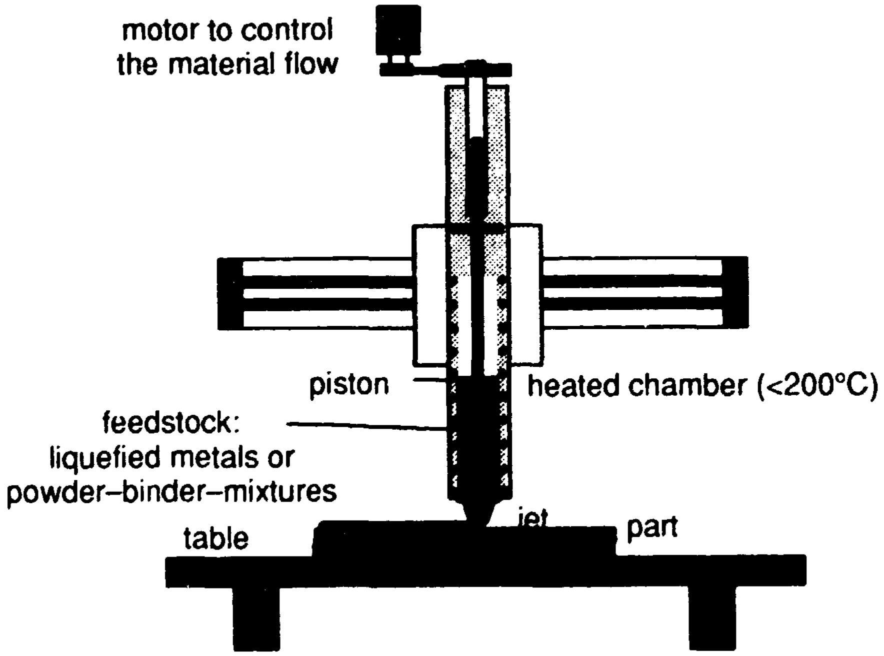


Figure 2.16

Work principle of laminated object manufacturing

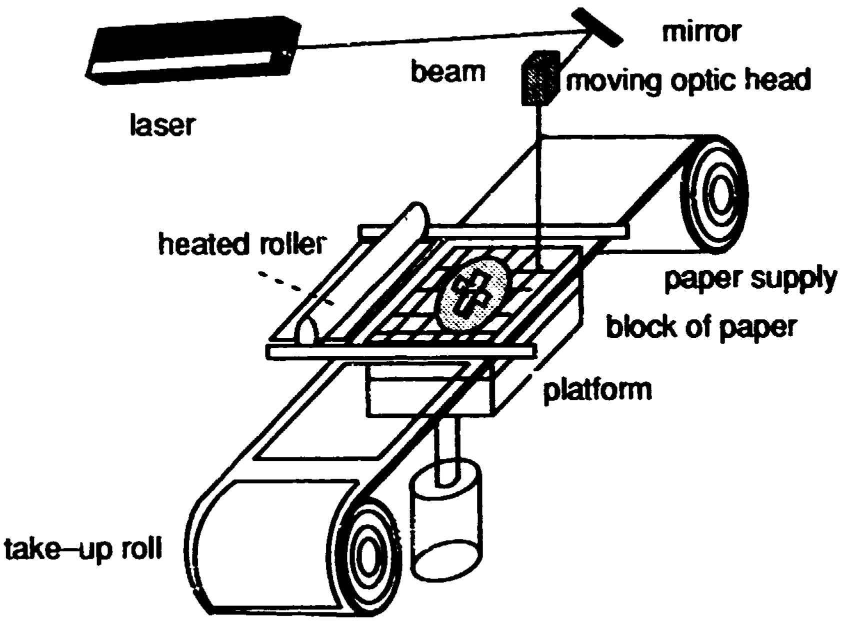


Figure 2.17

Selective adhesive and hot press process

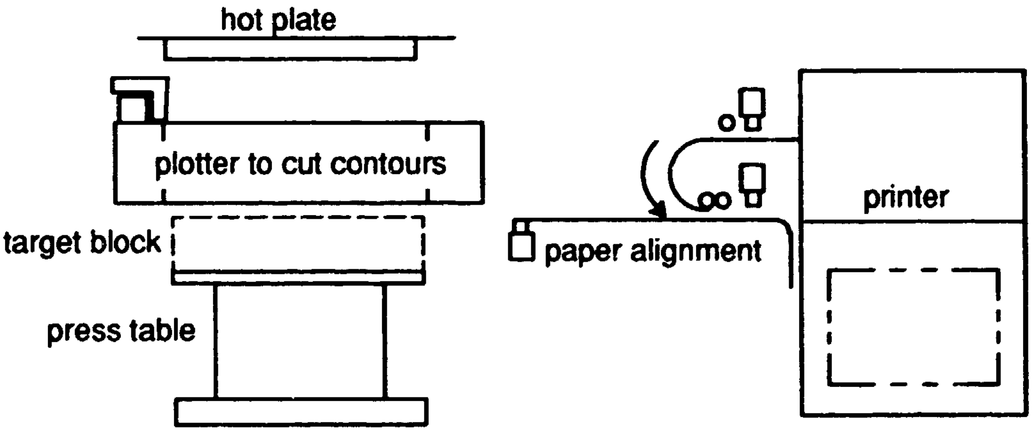


Figure 2.18

Slices produced with 5-axis water jet cutting without staircase effect

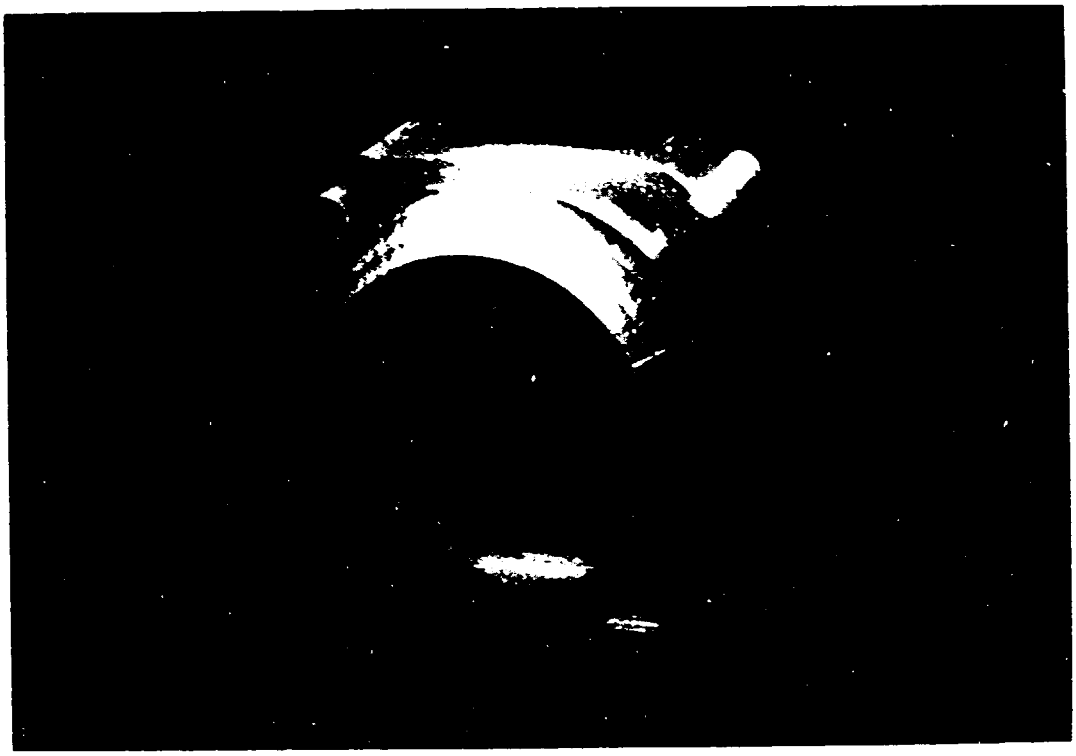


Figure 3.1

Data conversion and exchange in rapid prototyping

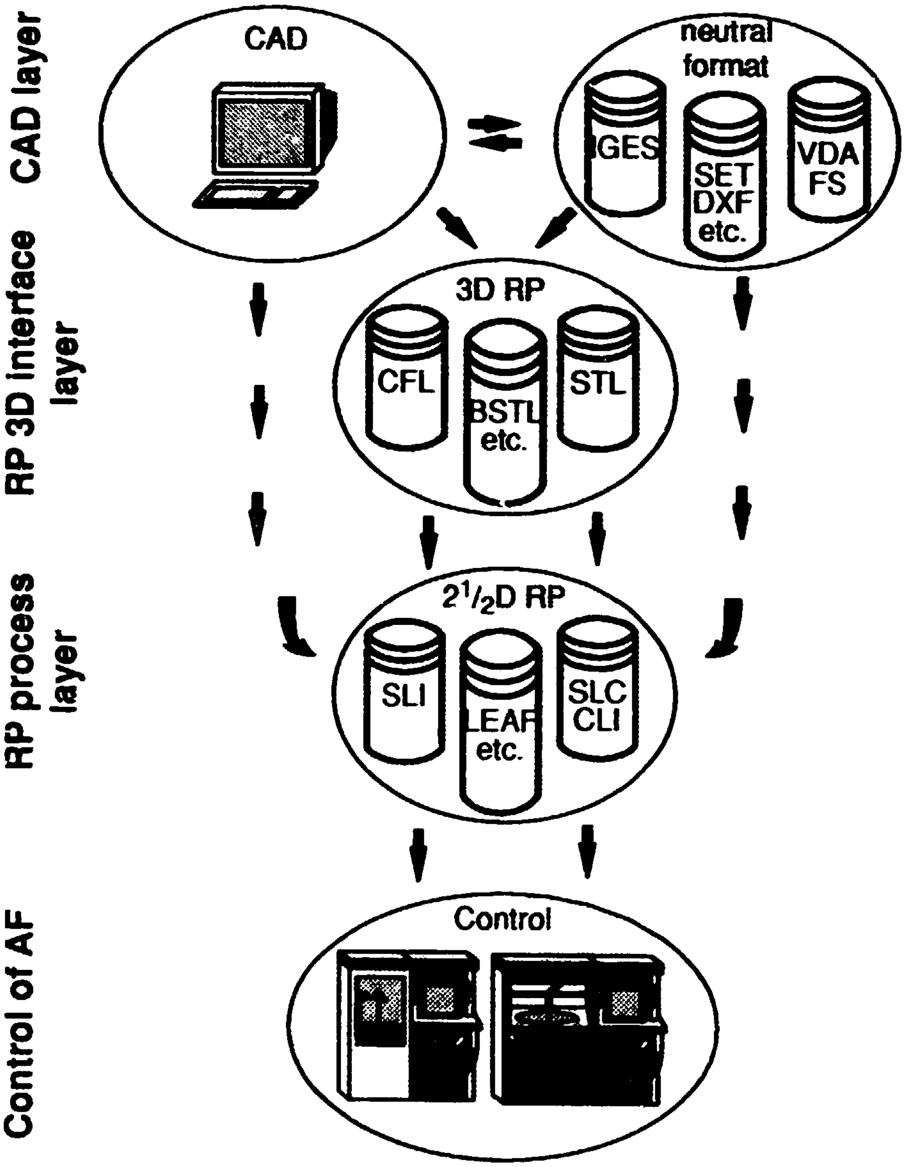


Figure 3.2

Correction of slice contours due to layer thickness and surface inclination

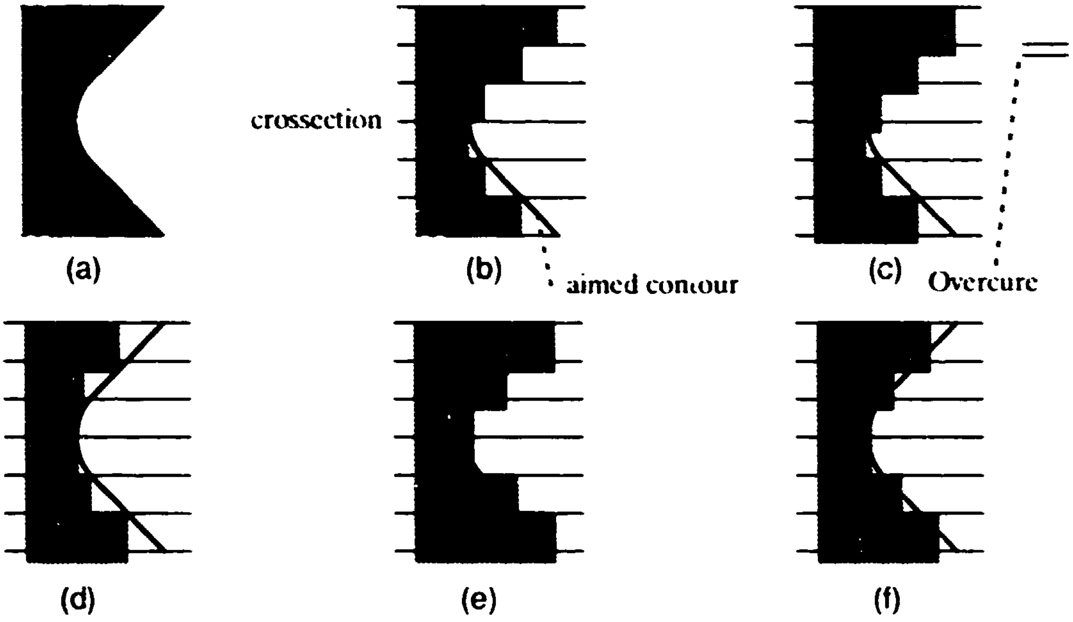


Figure 3.3

Software tool to correct borders of slices

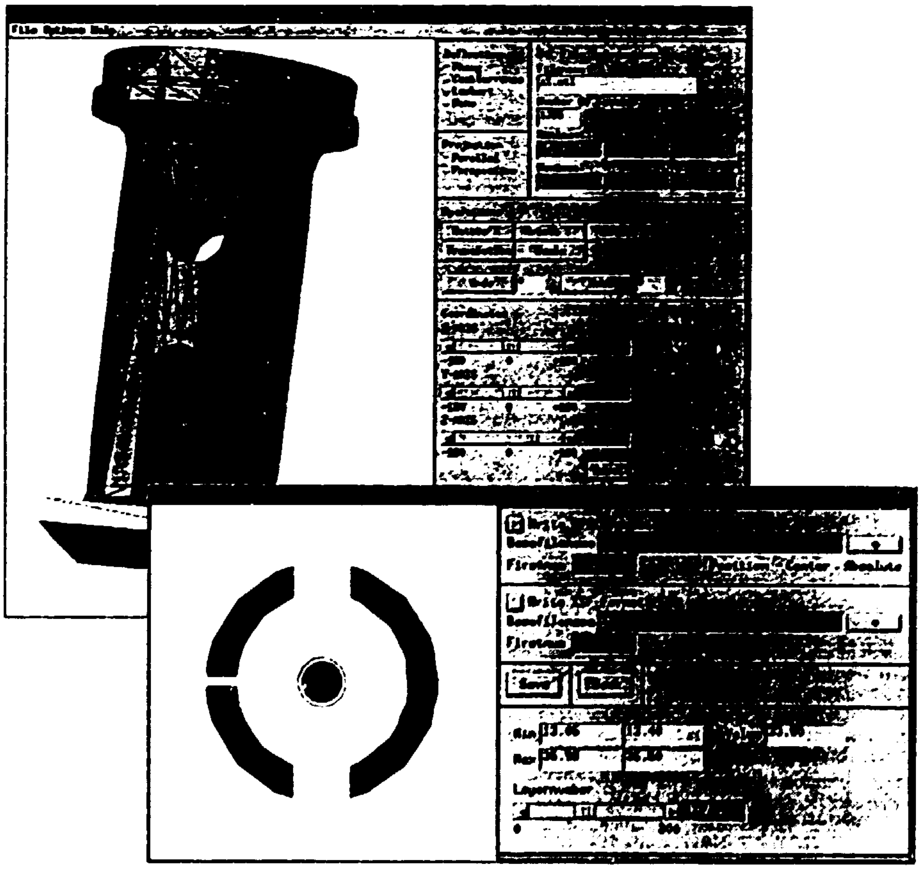


Figure 4.1

RP process selection house

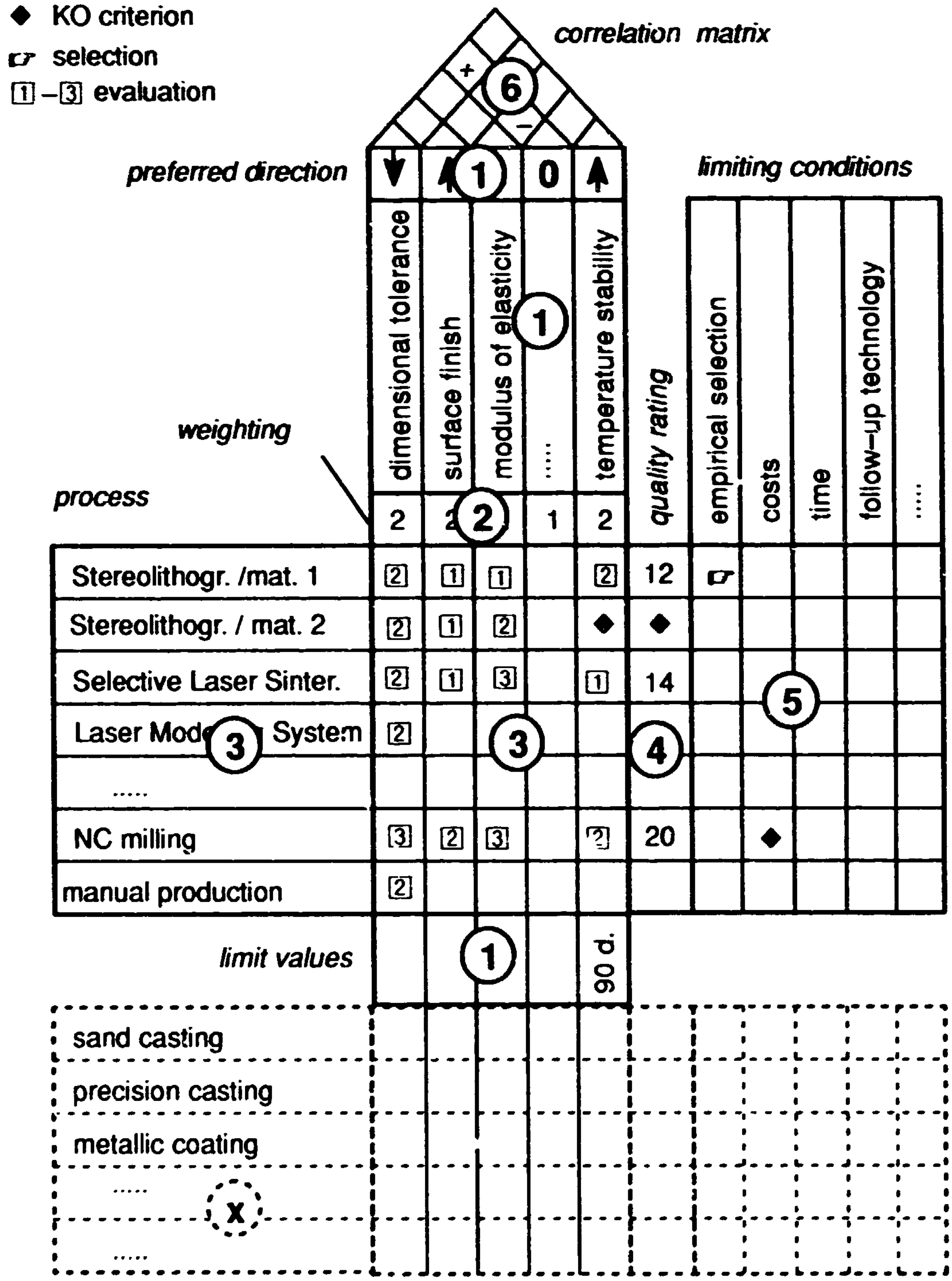


Figure 5.1

Vacuum casting

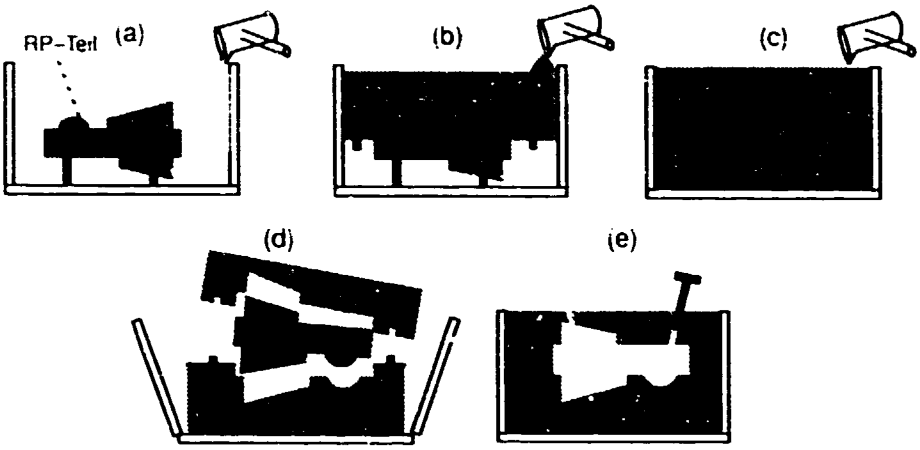


Figure 6.1

Fast iteration of process loop in rapid product development

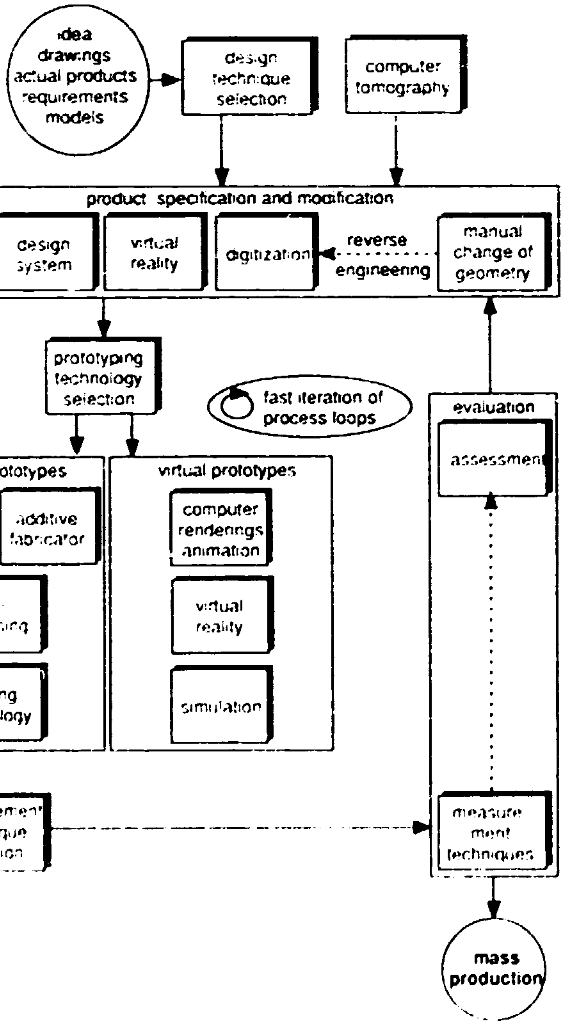
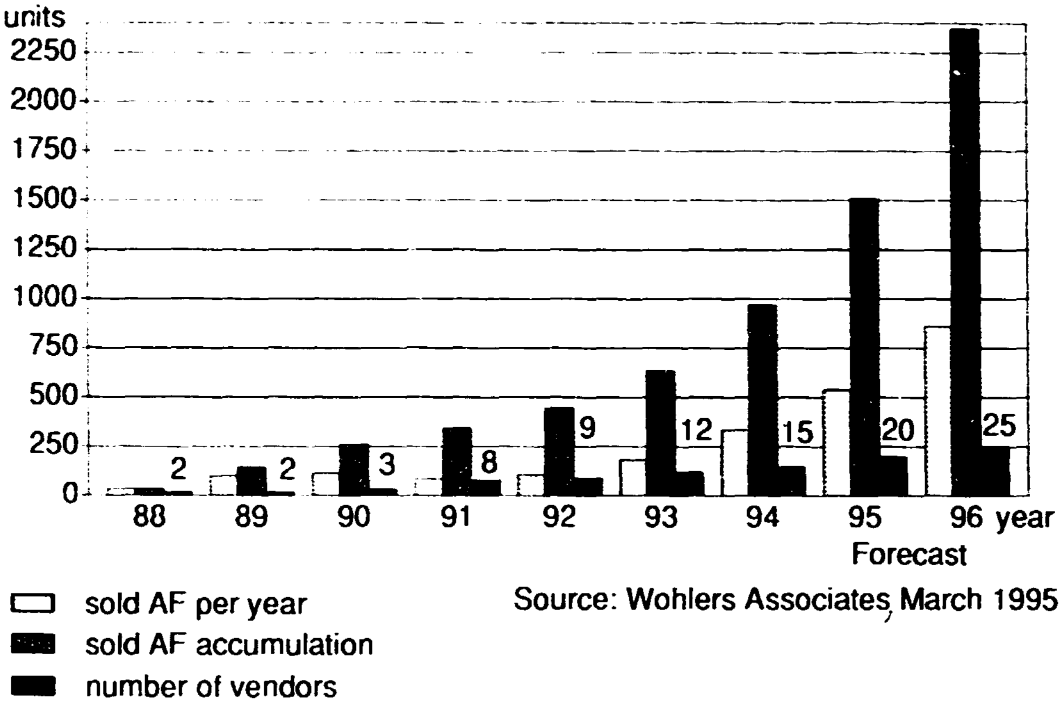


Figure 7.1

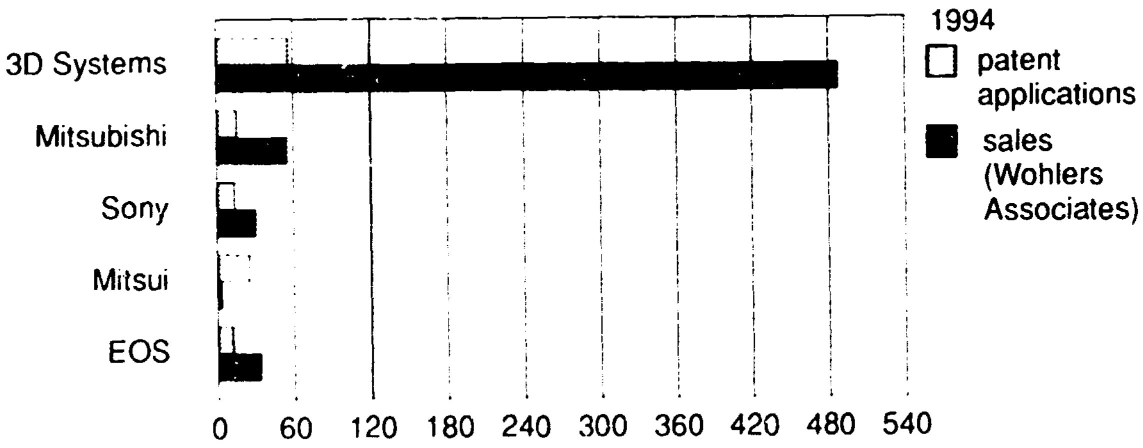
Sales of additive fabricators



Source: Wohlers Associates, March 1995

Figure 7.2

Sales and patents on stereolithography



B. NEW PROCESSES AND TRENDS IN DEVELOPMENT

Noncontact digitizing—a new wave in prototyping

Manufacturers can shorten product development by digitizing with optical image sensors so as to reproduce complex free-form surfaces with a high degree of accuracy. Pace Optical Test & Measurement, Phoenix, USA, has an optical sensor which combines Moiré techniques with triangulation methods to record up to 300,000 point co-ordinates from one viewing angle. These triangulation calculations surpass previous limitations of this technique by measuring complicated object attributes such as stepped features. Applications for optical digitizing range from copy-milling parts from models, surface reconstruction and quality control and assurance.

When two light-project grids, or gratings, intersect in space they create a Moiré fringe pattern of light and dark planes. As they intersect an object, these planes appear on the object's surface as contour lines which follow the topography of the object's surface. The reference grating, which is etched onto the lens of a chip camera within a recording video camera, creates the second grating. The video camera records the interference between the projected grating and the grating within the lens, with the resulting contour lines being recorded on video tape.

The limitations of this standard Moiré technique when used to calculate 3-D coordinates are that the distances to the generated planes are not constant, so that the distance or coordinates of at least one point must be determined using some other measuring technique. In addition, the contour lines may not be unique to a single feature, representing stepped features, different objects or complex surfaces, thus leading to a misinterpretation of the subsequent Moiré pattern.

Pace Technologies, Germany, have developed a system using a modified Moiré technique, called "Comet". It performs geometric analysis of the Moiré information by mathematically triangulating each pixel in the optical image into 3-D coordinates. The parameters that determine triangulation calculations include a basis line and two angles. The optical set-up of the sensor determines the basis line as being the distance between the centre of the projecting lens and the centre of the camera lens. The solid angle is the reference angle of each object point from the basis line and is defined by the pixel coordinates and the centre of the camera lens. A further angle defines the light-sectioning Moiré plane for each object point and is generated by a project rotating-line grating which modifies the light intensity at the object point. The video camera then records this modulation of brightness and is used to identify each Moiré sectioning plane. The values of the three combined provide a triangle for the system's computer to calculate the 3-D coordinates of a point.

One single view can measure the 3-D coordinates of up to 300,000 points on a fixed-coordinate system. Linear magnification or reduction adapts the field of view to the size of the object, or adjusts digitizing accuracy. Several scans are possible for large objects by altering the position of the sensor. Through partially overlapping scans, the system computer generates a point cloud of the entire object. The computer is designed not to accept points outside the focus range or any pixels that yield invalid data.

The accuracy of the sensor is high, due to the small triangulation angle which minimizes problems with shadowed regions of steeply angled features on the object. While being similar to other optical digitizers using an electronically switchable grating, this system with its rotating grating can deliver greater accuracy. The switchable LCD grating acquires image data faster, but the accuracy of this grating is 10 times lower due to the higher line density and precision possible with the fixed gratings of the Comet system. An LCD grating system works well in a mobile, flexible set up where low accuracy is acceptable.

As the system sensor acquires 3-D coordinates in a fixed sensor coordinate system, the computer can connect different views of one single large object to describe the entire surface. If a particular milling machine controls the position of the sensor, coordinates for measuring can translate into a single coordinate system. Thus, the size of the objects digitized is only limited by the available computer memory and capabilities of the CAD system. Normally, an entire surface requires 10 to 100 different partially overlapping views to completely digitize. The resulting point cloud, which contains 3 to 30 million points, needs 15 minutes to 2 hours to collect.

At present, there are three applications which could take advantage of optical digitizing:

Copy milling. This is an important application for modern tool- or mould-making facilities, it calculates machine-tool numerical control (NC) programming from the generated point cloud. Due to the short time needed to digitize an entire part, machining data is available quickly. This data typically machines a copy with a mean deviation of less than 0.02 mm from the original model. The digitizing system calculates the NC program in a background mode, allowing the milling machine and digitizing sensor to perform other jobs during data calculations.

Quality control and assurance. Due to the high data-acquisition rate and accuracy, optical digitizing can compare production parts or moulds to specifications. This application may require that the surface points be aligned to the design data by using best-fit approximations. Once the part is properly aligned, the computer-managed milling can calculate deviations between the part and the part-data file and then determine the acceptability of the manufactured part. Deviations would result in modifications to the original NC program, which would then machine a more accurate mould or product.

Surface reconstruction. A number of CAD/CAM software systems apply a variety of strategies to reconstruct surfaces from point data. At present it is possible to automatically generate surfaces with relatively low quality. Where the surface must have a high quality, such as car bodies or household appliances, computer operators normally have to make several modifications to reconstruct the surface, which requires 200 megabytes of memory, or greater, and built-in visualization tools in the CAD package. (Source: *American Machinist*, May 1995)

Laser metal deposition process

Los Alamos National Laboratory, USA, is developing an automated one-step method for fabricating complex metal parts by fusing metal powders in the focal zone of a high-energy laser beam. This direct metal deposition process is called "Directed Light Fabrication" (DLF). It does not use a mould, pattern or forming die and produces a fully dense metal part which is shaped to within a few thousandths of a centimetre of final tolerance. This DLF process combines computer-aided design and manufacturing technology, and laser cladding technology as well as rapid prototyping technology to directly deposit metal to form a near-net-shape component from a digitally designed solid model. The straight surfaces and high-dimensional accuracy of the parts thus produced compare favourably with the metal build-ups made since the 1930s using oxyacetylene, tungsten or metal inert gas, plasma or laser welding processes.

The main components of the DLF process are the Nd-YAG laser, a metal-powder delivery system and a computer-controlled laser beam positioner. The fabrication of a metal part starts with a 3-D solid model computer design from which a positioning code, including laser control and other system commands, is developed and sent to the DLF positioning system during fabrication. The positioning system, which is programmed for multi-axis control by the computer code, moves the focused laser spot along the contours of the part as metal powder is fed into the beam spot and fused. One planar layer is formed at a time on a supporting base plate which is removed after completion. Unused powder which falls outside the laser beam is recovered for reuse. The next generation DLF will automatically recycle the unused powder to the powder hopper so that no waste is generated. As partially fused powder particles stick to the sides of the molten part of the deposit, the surface can be rough. Further development to control the process variables is expected to result in a smoother as-deposited surface. It is anticipated that additional finishing operations may be required to polish the surface and thus achieve close geometric tolerances.

Parts which have so far been made using the DLF process include tubes, channels, hollow I-beams, plates, cones attached to tubes and rods. Each part was made without requiring a part-specific tool for each shape. For example, a separate extrusion die is normally required to extrude many shapes; for the DLF process, only the computer model is modified to change the output shape.

With further development of this technology, there is no limit, in principle, to the geometry of the parts that can be fabricated. Hollow cavities, curved contours on the inside or outside of a part, integral flanges, tubes and cylindrical projections will be formable without welding. The dimensional tolerances of the part are determined by the size of the laser focal spot, the size of the pool of molten metal and the processing parameters, whereas the process economics are determined by the powder feed rates, the speed and the laser energy.

Use of this rapid prototyping process will mean that it will be possible, within a few hours, to have a part in-hand, that would normally have required weeks or months to make using conventional methods. A designer will be able to test in service a specific part design which has been fabricated using the DLF process, as it will have full structural properties. It can then be iterated by changing the solid model of the part on the computer. Conventional methods would require building a pattern, a mould or a forming die prior to making the new part.

There are other advantages to the DLF process. Laser-processed powders will not have the problems of macro-chemical segregation which is found in conventional casting and thus will not require homogenization and grain refinement via heat treatment, forging or extrusion of a casting. This obviously represents a large economic advantage in the capital equipment costs required. The precise build-up of laser-fused powders potentially offers new methods of fabricating parts with tailored properties. Strength, ductility and density gradients can be created by applying different metallurgically compatible alloy powders on different areas of the part to accommodate high-stress concentrations, density variations, etc. Perhaps most importantly, the DLF process is non-contaminating because only the laser beam contacts the powder and processing can occur in highly controlled atmospheres.

Development is continuing at Los Alamos to extend the application of DLF to a wider range of materials. Industry participation in collaborative research and development is being sought.

Further information can be obtained from: Gary Lewis, Group MST-6, Mail Stop G770, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA. (Source: *Mat Tech*, 1995 10:43-58)

Advantages/disadvantages of RP versus CNC

Rapid prototyping techniques have collectively come to be called additive rapid prototyping (ARP) because all techniques build up models from numerous thin layers of materials. ARP brings huge benefits. For some kinds of parts, prototyping has been sped up as the process is fast and gives designers physical models which reveal form and fit errors quickly. In addition, those parts for which ARP is best suited represent a substantial volume of new products. However, even with the euphoria about ARP, one must not forget that computer numerical control (CNC) has been capable of rapidly making prototypes for almost 20 years. Some engineers feel that ARP has not always kept its promise as ARP cannot always match the accuracy available with CNC. A study is under preparation to compare real ARP results against the established accuracy of CNC machining. It is hoped that the outcome will show some real measure of relative accuracy.

At present there are five main kinds of ARP systems in production: stereolithography (SLA), solid ground curing (SGC), selective laser sintering (SLS), laminated object manufacturing (LOM) and fused deposition modelling (FDM). SLA was the first system and was originally fore-seen as a way in which to obtain quick 3-D parts directly from solids CAD data. Accuracy, strength and surface finish were not of the highest priority. These initial 3-D parts were designed primarily to be models that a designer could hold and feel to see if CAD geometry would turn out as intended. Pressure was exerted on the manufacturers of the first machines to improve some parts and as a result, systems have improved. Materials used today are stronger, resist building distortion better and give faster build times. In addition, computers have become more powerful, allowing better slice-and-build programs that have reduced shrink, warp, sag and curl. Some systems can now produce faster, better parts for secondary casting procedures. Developments exist so that rapid manufacturing can be done using these systems; however, reality may be rather different, for many physical and chemical reasons.

ARP has a number of other limitations. Engineers using ARP have a finite number of materials from which to choose. It is also best suited for small models 80 per cent of all ARP machines have 10x10x10 inch tanks. Other machines can manage models up to 30x20x30 inches. The surface finish may require a significant amount of hand sanding should the model need a high-gloss finish.

However, ARP can produce complicated parts that CNA cannot, for example, a prototype of an auto exhaust manifold with accurate inside and outside surfaces. The strength of ARP is probably in medium-sized plastic parts and wax patterns for various secondary casting methods. Other than these, product designers must rely on a combination of the old and the new, which is now being called fast prototyping. This method combines traditional fabrication with complicated insert sections handled either with ARP or CNC-machined parts. The combination of the two techniques is a way around some of the drawbacks of the SLA method. ARP is not adept at faithfully reproducing large flat areas.

Capabilities of prototype systems

Application	Traditional model/prototype CNC shop	Additive RP system or servicve bureau
Soft prototyping		
Visual images on solids CAD	Some	Some
Hard prototyping		
To hold and feel	Yes	Yes
Plastic prototypes		
Miniature	Yes	Limited
Medium	Yes	Yes
Large	Yes	No
Clear/tinted	Yes	No
Flexible	Yes	No
Metal prototypes		
Machined	Yes	No
Castings	Patterns	Patterns
Sheet metal	Yes	No
Ceramic prototypes	Patterns	Patterns
Wood prototypes	Yes	No
Working prototypes	Yes	No
Field test prototypes	Yes	No
Focus group prototypes	Yes	No

At the same time there have been major advances in computer-driven machine tools, which can be seen as a spin-off of the development of ARP. CNC has now matured to a point where it can serve as a viable alternative to ARP. Traditional model and prototype shops today will have powerful CAD/CAM software on large computers with 16 megabytes of memory and more than 500 megabytes of hard disk. Very often they may be able to put a tool path to a client's data file in a few hours. CNC can then create three, four, or five-axis, mathematically based surface contouring. The machine will produce a tight, precise, sturdy part in ABS, polycarbonate, composite, aluminium or other materials. As compared to ARP, such parts are not fragile and need no support to fight sag, warp or curling. Another advantage of CNC is that, depending on the size of the parts, it may be possible to CNC a dozen copies in design material faster than building and finishing a similar number with ARP.

Each technique has its strengths and weaknesses designers should be aware of the limitations of each before a decision is made. Many prototyping service bureaux are adding CNC machines to their ARP machines as they are beginning to see the benefits of combining the two methods. (Source: *Machine Design*, 7 November 1994)

2-D Rapid Prototyping

There are times when using stereolithography, or a similar means of producing complicated 3-D shapes is too advanced, such as when wanting to produce circuit boards and sheet metal, which only require a 2-D shape. It is now becoming practical to prototype these components using a low-power laser. A laser can cut a full-sized prototype of a circuit board from a 0.062 inch thick card stock. The prototype produced will have all the necessary holes, notches, break-away tabs and routered shapes of the finished board. In addition, the prototype can be engraved with the silkscreened component designation pattern of the finished product. In this way, engineers can evaluate most of the mechanical aspects of the printed circuit board (PCB) by inspecting the 2-D prototype. The same technique can be used to generate inexpensive mock-ups of sheet metal components. For example, enclosure designs consisting of two sides, top, bottom and back can be cut from card stock or plastic, complete with holes, vent hole patterns and cutouts. By putting the pieces together, a prototype enclosure is formed. Engineers can thus confirm that the mechanical components fit within the enclosure and that all mounting holes are properly located. By adding fans to the prototypes, air flow can be checked if required.

Two-dimensional prototyping typically starts with the database from a CAD package from which the user will generate an x-y plot of the component to be prototyped. The plot can be in any compatible graphic representation. This plot is then forwarded to a service bureau which will produce the prototype, if not done in-house. In some countries, plot data can also be phoned in via modem and the turnaround can often be overnight. There are basically two sources of data for 2-D prototypes. One consists of the arcs, lines and circles that are to be cut to form the component. The other is data that is to appear on the component (such as part numbers), but which is not cut through. Different colours can distinguish the two different types of data. Alternatively, cut and engraving data can reside in different plot files. Typical 2-D prototyping materials include paper, card stock, plastics and wood with a maximum thickness of around 6 mm. Accuracy is usually 0.002 inches. In the absence of special compensation, hole sizes are approximately 0.007 inches larger than plotted due to the size of the laser beam. The price of the prototyped component is set by material costs and laser cutting time. Often, customers are allowed to provide their own materials, thus lowering the costs. Some service bureaux are limited in the sizes of components they can offer due to the machinery available.

Two-dimensional prototyping has some advantages for 3-D components. For instance, an angle bracket can be cut in a flat form from plastic which can then be heated and bent into its final configuration. This technique can also aid the evaluation of stampings without the cost of making them in metal.

The relatively low cost of 2-D prototyping can enable engineers to evaluate numerous design options. For example, in the design of an instrument front panel, five different arrangements for the controls with knobs, switches and displays installed can be prototyped. Such full-size mock-ups can be used as inexpensive sales aids and help meet trade show display deadlines. (Source: *Machine Design*, 9 March 1995)

RP using stratified object manufacturing (SOM)

Since 1986 when the first rapid prototyping systems were introduced, the demand for prototypes that can withstand mechanical and thermal stress has been growing. Direct manufacture of metal prototypes has not been possible in most methods used in industry despite the high investment and handling expense. Until now, accuracies achievable depended greatly on the method, the component geometry and the experience of the user. Stratified object manufacturing (SOM) is a possible new manufacturing strategy for the direct production of functional prototypes, which is based on existing computer-aided techniques and makes particular use of the potential of high speed cutting (HSC).

MEC GmbH, Germany, has developed this new rapid prototyping method with the essential difference to known generative rapid prototyping methods being that existing 3-D CAD data are not prepared for 2-D cutting of thin layers, but rather for a 3-D cutting using CNC manufacturing methods. This procedure has been called stratified object manufacturing (SOM) because of the new procedure, with two sided 3-D CNC machining of plates having different thicknesses. Conventional 3-axis or 5-axis milling is primarily used as the machining method.

Conventional rapid prototyping methods require the following steps to produce a functional prototype: data preparation, improvement in the surface quality and slice process, construction process, manual finishing of the model, subsequent casting process and finish machining. The steps of the SOM method are limited to data preparation, for instance division of the CAD geometry into plates followed by surface division in accordance with milling criteria, and CNC machining of the finished part, including performance of the required joining operation. Complete machining in one company provides a greater flexibility and reduces interfacing problems.

The nucleus of the SOM method is the division of 3-D CAD data into partial geometries referred to as plates. An additional surface preparation makes two-sided conventional CNC machining possible in various work fixtures. The material used is usually unmachined and is available in rolled or cast quality. The initial thickness is greater than the actual plate thickness because of the required bracing function in the first machining operation and for the necessary machining allowance in the second machining operation. The construction process is differentiated between three steps which depend upon the complexity of the component and the required profile available, and the number of plates resulting from this and which must be performed a number of times. These steps are: (1) initial machining operation after face milling of the joint surface and the attachment of reference elements, the actual machining of the component surfaces takes place; (2) joining and bracing adjacent plates are connected to one another after machining. Local bracing material is inserted in the thin webs or in geometry islands that occur between the individual work steps; (3) second machining operation the component surfaces are machined after face milling to the desired thickness.

The main features of the SOM method are a division of the component geometry into two-sided machining of plates without undercut, meaning that the generative and abrading manufacturing methods are combined, and it is a method that using conventional 3-D CNC manufacturing components can solve the problems involved with bracing and chucking (initial machining operation of a plate with machining allowance, second machining operation when joined, possibly with bracing material).

Based on these features, the following advantages result for prototyping manufacturing: (a) accuracy and surface quality can be achieved which correspond to CNC quality and are independent to a large degree from the size of the component; (b) a flexible combination of manufacturing methods and different materials is possible; (c) various methods for surface machining and changing the material characteristics can be used in areas not otherwise accessible; (d) the method allows the manufacture of instruction models that can be disassembled; (e) the environmental impact is slight due to the direct manufacture of a finished part; and (f) besides the primary direct CNC manufacture of prototypes, which can be subject to stress, even investment patterns for subsequent casting processes with local machining allowances can be produced for target materials that are difficult or impossible to machine.

Prototype manufacturing using the SOM method seems to open new application areas when used in conjunction with high-speed milling. The advantages, besides the reduced machining times, are the achievable improved surfaces and the machining of thin-walled workpieces with good dissipation of the machining heat. (Source: *VDI-Z*, Duesseldorf, March/April 1995)

Faster rapid prototyping

3D Systems, Valencia, CA, USA, has introduced its Stereolithography Apparatus Series 500 and 30H which increase part-building speed by incorporating a high-power laser, whilst continuing to produce high accuracy levels needed for complex geometry. Based on part geometry, the SLA500-30H increases part thoughput by up to 36 per cent over the previous series making it suitable for building models, prototypes or patterns with epoxy resins. (Source: *Machine Design*, 15 June 1995)

Rapid prototyping bureau

The Automotive Design Centre, which is based at Queen's University, Belfast, Northern Ireland, aims to provide CAD, CAE and rapid prototyping services to engineering companies working in all sectors. In addition, the Centre offers CAD services ranging from simply transferring existing paper-based drawings into 3-D CAD, through to design for production from the initial concept stage. The Centre collaborates with other groups at Queen's University working on internal combustion engines, microelectronics and polymers. (Source: *Engineering*, October 1994)

Computer Aided Rapid Prototyping project (CARP) results

An example of the work produced by the Computer Aided Rapid Prototyping project was recently exhibited. It was a prototype close-coupled V6 automotive catalyst unit, comprising a cam and manifold, which was cast in stainless steel without the need for any tooling.

The starting point for the work was the initial specification for the internal shape and layout of the unit, which was supplied in the form of a CAD model. From this internal layout it was decided that the finished unit should be assembled in two parts the catalyst can, into which the catalyst brick would be assembled and an integral unit forming the catalyst end cap and exhaust manifold. Complete designs were developed by Webster Mouldings (UK), using Delcam's DUCT CAD/CAM software, by superimposing a standard metal wall thickness onto the internal geometry and then adding flange and joint details. Data for the RP process was generated from Duct. Models were then produced using the Helysis laminated object manufacturing system and the DTM selective layer sintering system at Leeds University (UK). Runners and risers made from wax were added to the prototypes. The complete assemblies were moulded using the investment casting process followed by a controlled burnout process which ensured complete removal of the pattern whilst maintaining the integrity of the mould structure. Casting and mould break-out were carried out in the same way as for traditional investment casting. (Source: *Engineering*, October 1994)

Prototyping machine building with ink-jet methods

BPM Technology Inc., Greenville, SC, USA, has introduced its Personal Modeler which uses a drop-on-demand piezoelectric jetting system to shoot or jet microscopic particles of a molten thermoplastic. The material freezes when it hits the object under construction, and models are built layer by layer, as with most other rapid prototyping methods. It uses a single 5-axis robotic nozzle and can produce thin, hollow-shell models of any geometry, including those with horizontal surfaces.

This process has several advantages over other rapid prototyping methods, for instance, the unit constructs a horizontal surface or skin by automatically building support structures when needed. The non-toxic thermoplastic needs no special handling or ventilation; by operating at the 55 dBA sound level, the machine is suited for office environments.

The prototyper imports the widely used .STL file, automatically corrects file irregularities and creates the necessary breakaway supports, and builds the model free-standing and unattended within hours. No postcuring or solvents are required and the models are compatible with investment casting. In addition, the machine builds models in either a default hollow-shell mode or in the stronger internally cross-hatched form. (Source: *Machine Design*, 11 May 1995)

Experimental fabrication of castings using RP

The Akita Prefectural Industrial Technology Center has applied stereolithography to prototype master castings for the first time. This process enables them to build complicated parts which cannot be produced rapidly by conventional machining techniques, and is presently used as a tool for producing prototype evaluation models. The next-generation version of this rapid prototyping process was applied to the master models for producing precision castings. Research has developed investment casting technology using the rapid prototyping parts to replace the conventional wax model, and to pump vanes with 3-D curved surfaces, which were cast successfully and were previously difficult to produce by existing manufacturing processes.

The new casting method comprises the following processes: (1) designing the cubical shapes of castings by 3-D CAD; (2) slicing the design models into cross-sections from 0.1 mm in thickness by slice computer; (3) solidifying the photo-curable resin with a laser beam into a cross-sectional shape, and building the parts sequentially by rapid prototyping machine (SLA 250, 3D Systems Inc., USA); (4) coating the model with a ceramic slurry as in the lost wax process and producing the shell model; (5) sintering the shell model and combusting the parts to obtain the casting mould; and (6) pouring molten metal into the mould to obtain the finished casting.

This new method requires no wax model or wood mould for green sand as with the conventional casting method and enables castings of complicated shapes to be cast rapidly and at a lower cost.

The Center plans to incorporate this rapid prototyping process and CAD/CAM/CAE into an integrated network system with the aim of developing an advanced process for manufacturing moulds of high added values within a short time.

Further information can be obtained from: The Akita Prefectural Industrial Technology Center, Machine & Chemistry Div., 4-11, Sanuki, Aza, Shinya-cho, Akita City, Akita Pref. 010-16, Japan. (Source: *JETRO*, March 1995)

RP to help detect stress on jet engine blades

One of the more novel applications for rapid prototyping technology is to design rotor blades for jet engines. The French aircraft engine manufacturer Snecma (Société Nationale d'Etude et Construction de Moteurs d'Aviation) uses optical stress analysis on engine blades and disks in conjunction with stereolithographic models.

The key to the technique is the fact that the epoxy resins from which the stereolithographic models are made have optically active properties. Snecma plans to make an SL model of a rotor blade, then stress it under centrifugal or external loadings such as torsion, tension, or pressure. Loading should take place in an oven heated to around 100° C, which is warm enough to put the epoxy into its glass transition phase, changing from an elastic to a rubber-like state.

When cooled, the stress patterns on the part freeze. Snecma can then slice the model apart at each critical stress zone and examine the cross-section under polarized white light. When viewed through an analyser, iridescent colour fringes, which indicate stress levels, become apparent.

Snecma is still running preliminary tests on the method. The next step will be to eliminate the mould step, making stress tests on the epoxy part directly. (Source: *Machine Design*, 10 October 1994)

Rapid prototyping as a model in lead time savings

The Helisys laminated object manufacturing (LOM) rapid prototyping service, which is offered by Umak (UK), has significantly reduced lead times for the electric motor manufacturer, Brook Crompton (UK). The technique also minimized the risk element into developing a new range of high-efficiency electric motors. The project team used LOM to produce highly accurate laminated paper models of the motor frame and end covers. The models were then used as sacrificial patterns for the aluminium casting of the prototypes. Once produced, it was possible for the company to embark on a series of prototype development trials prior to finalizing the frame production tooling. The Helisys LOM system uses a single laser to cut thin paper-type materials in sheet form to create solid objects of virtually any shape and complexity. (Source: *Machinery and Production Engineering*, 17 February 1995)

Computervision RP interface

Computervision has announced its RP interface which functions integrally with its CADDS 5 design and manufacturing system. This new interface allows model geometry, which is created within the package, to be directly outputted to a variety of RP systems. This program allows designers to create and edit complex surfaces with the use of a mixture of solid modelling and NURBS-based surface design. Access is through an easy-to-use menu system; the interface produces files in STL, a standard format for RP. The user is able to define the orientation of the files, whilst the output can be displayed as shaded images. (Source: *Automotive Engineer*, October/November 1992)

New LOM materials from Helisys Inc.

Helisys Inc. (Torrance, CA, USA), has introduced a new High Performance LOMPaper (LPH). The company claims that it offers LOM users significantly reduced build times and improved part accuracy and flatness. Helisys has also developed a new proprietary adhesive which they say offers LOM users faster bonding speeds, reduced internal stress, and improved Z-dimensional strength. Helisys also now offers a user guide including reliable parameters and procedures for all currently available LOMaterial products marketed and sold by the company. It also includes optimization and advanced techniques to help users get the most out of their machines. (Source: *Rapid News*, Vol. 3, No. 2, 1995)

Composite material for Rapid Prototyping

DTM Gmbh (Hilden, Germany) has introduced the first composite material for use in rapid prototyping. Laserite LNC-7000 (Nylon Composite) is a glass-filled nylon that, according to the manufacturer, exhibits the highest properties of stiffness and heat resistance of any material used in rapid prototyping. The company also say that the nature of the material is such that it can produce parts with very fine features which are strong enough to withstand functional testing requirements. (Source: *Rapid News*, Vol. 3, No. 2, 1995)

Rapid Prototyping with no intermediate interface

F&S StereolithographietechnikGmbH (Borchen-Alfen, Germany) has announced the availability of a stereolithography system that, according to the company, creates unfaceted three dimensional objects with no necessity for an intermediate interface such as an STL file. The system directly slices the CAD model, meaning that the cross-sections are therefore generated directly from the mathematically precise CAD model. The company chose the Hewlett Packard Graphics Language (HPGL) format as the output format for the cross sectional data, as it is used as a standard for plotters and printers and is support by all CAD systems.

The company have also developed a stereolithography machine called the LMS (Laser Manufacturing System) which runs using the direct slicing methodology. The company claim that by using a patented recoating mechanism and a special exposure style, the building times on the LMS can be shortened when compared with other processing times. (Source: *Rapid News*, Vol. 3, No. 2, 1995)

Vacuum casting resin developments

MCP Equipment (Stone, UK) manufactures a range of polyurethane and epoxy resins for vacuum casting in a variety of colours, hardnesses, strengths, densities, and temperature resistances. Recent additions have included the MCP 8090, which it is claimed, is one of the highest temperature-rated vacuum casting resins available. With a cured temperature resistance of 100° C, the company expects that the resin will bring more temperature-sensitive components within the scope of vacuum casting. The material is milky-white in colour, largely translucent and a two-stage polyurethane resin with the two constituents mixed in a 1:1.5 ratio before being cast into a silicone-rubber mould under vacuum. (Source: *Rapid News*, Vol. 3, No. 2, 1995)

Personal modelling office machine

BPM Technology, Inc. (Greenville, SC, USA) has introduced the Personal Modeler computer peripheral office machine which operates at the "push of a button" and produces relatively economical real physical models which can be produced from any available solid modelling CAD program.

The company has developed and patented a modelling technique called the Ballistic Particle Manufacturing, which uses a drop-on-demand piezoelectric jetting system to shoot microscopic particles of environmentally safe molten thermoplastic that freeze when they hit the object being built. The process has been called "Digital Microsynthesis". This process is relatively clean and quiet as well as being economical as it uses the exact amount of material required to build a finished model without any waste. In addition, during the model construction period, there is no necessity for operator attention, thus reducing overhead costs associated with its use. (Source: *Rapid News*, Vol. 3, No. 2, 1995)

Direct Shell Production Casting (DSPC)

Direct Shell Production Casting (DSPC) is a process involving manufacturing ceramic moulds, resembling those used for investment casting, directly from CAD files. The advantages of castings, combined with computer technology, yield complex designs to near-net shapes with little waste. The process is flexible, easily incorporating design changes, eliminating the need to maintain patterns or dies, and removes tooling and set-up times for machining moulds. It can integrate cores, allowing the moulding of hollow parts.

This new technology, brought to the market by Soligen Inc. (Northridge, CA, USA), was derived from a process known as three dimensional printing which was developed at the Massachusetts Institute of Technology. At present it designs mould production equipment capable of manufacturing short-run production metal parts and prototype moulds and dies for die casting and injection moulding. It is not intended for mass producing investment castings as conventional casting methods may outperform DSPC in certain cases by producing parts more quickly and economically. In addition, the new process lets investment casters combine integral cores and eliminate assembly, resulting in weight savings without a loss of strength by providing structural integrity. Material options can expand because any castable alloy can be used, including ones that were impossible to forge, or too difficult to machine. There is less sensitivity to alloy cost since integral designs often require less material.

Part-design research is continuing using knowledge and experience gained to produce intricate aluminium die casts whilst at the same time improving accuracy and durability. (Source: *Machine Design*, 10 August 1995)

First commercial solid-state laser

EOS GmbH (Munich, Germany) has recently announced the availability of its STEREOS MAX 600, the first commercial laser-stereolithography system with a solid state laser. The company say that the laser uses approximately two per cent of the electrical energy compared to a gas laser of the same output power and does not require any water cooling. The lifetime is reported to be around 10,000 hours, and as well as being economical to run, is able to achieve high building speeds. (Source: *Rapid News*, Vol. 3, No. 2, 1995)

Metal prototypes in two weeks

Schneider Prototyping GmbH (Bad Kreuznach, Germany) says that through the use of the Cubital-based SoliCast process, designers can see their CAD files turned inexpensively into metal prototypes in two weeks. Using Solicast, moulds are investment-cast around Cubital models in-house. The company says that its proprietary methods completely consume the polymer resins that make up the models, leaving a void that can serve as a casting tool. The disposable prototypes are generated using a Cubital Solider 5600 machine and it is claimed that metal prototypes can be produced in half the usual time, at half the usual cost. (Source: *Rapid News*, Vol. 3, No. 2, 1995)

Pattern-making experience with rapid prototyping

It is not only large companies that have to take the first step in making use of new technologies. The traditional pattern- and mould-making company Hermann Bubeck KG (Germany) has been innovative in this field. Until the 1970s the company was exclusively concerned with the manufacture of foundry patterns. A decisive step was taken with the purchase of the first measuring machine which enabled the company to expand its services. Since 1986 the structure of the company has been adjusted to include CAD/CAM technologies. Normal working procedures today include digital acquisition and computerized preparation of patterns using measuring machines and planar feedback. Instead of sending drawings they use teleprocessing via ISDN. In 1994 the company was one of the first pattern-making enterprises to commission the German EOSINT 600 laser-sinter-plant. Only one week was required for installation and training on the use of the system. Patterns are mainly produced in polystyrene, which is suitable for investment casting as it fits with the normal coating and the melting-out process well. Once checked, the polystyrene parts are dipped in wax to achieve a good surface, whereafter they are delivered to the investment casting foundry which adds wax ingates, glued to a cluster and entered into the coating process. The company discovered that for vacuum casting processes it was particularly successful when the patterns were dipped in epoxy resin enabling a good machining of the surface and thus the production of good silicon moulds. (Source: *Giesserei* 82 (1995), No. 15, p. 539)

New dimensions for solid modelling

With solid modelling, a design can come to life within minutes with a 3-D clarity that is difficult, or even impossible, to achieve with drawing technology. As a company builds on its modelling experience, other advantages will appear, such as the easy reuse of existing models in new designs, change orders take place more quickly and manufacturers benefit because they can more easily develop accurate jigs and fixtures before they reach the shop floor. As with any transition, becoming productive using solid modelling involves effectively managing change. A good guide to manage this could be a well-supported training focused on anticipated tasks, retaining investments in 2-D data, and bringing users to greater levels of responsibility. Even though the company may possess the hardware, the staff need to be trained to use it properly.

The most effective training could start with a select group of people in a pilot programme where the software is learned with specific emphasis on features that the user will be most frequently confronted with. This training could be rudimentary or more involved, depending on the level of skills of the staff to be trained. Staff have to learn that practically every process associated with 2-D design will change in the 3-D solids world. In 2-D, the drawing is the master; with solids, the geometric model is the master and the drawings are part of the documentation.

As with any new system, support is essential. This can take the form of providing ready answers for problems that appear, thus preventing frustration among new users. Management attitude may also need change, to become more open to change and new ideas. The pilot programme should be used to produce a specific design for something that the company will produce, and not last for longer than six months. The experience gained can then be transferred to other departments within the company, gradually enabling the new teams to gain from the experience of the pilot programme, to gradually combine 2-D techniques with solid modelling.

The use of solid models allows design engineers to optimize qualities such as weight by iterating designs through finite-element studies. Eventually design engineers can use solid models on which to generate numerically controlled data for certain parts. Further, the engineer will manage tasks previously handled by additional staff, such as paper prints and documentation, through product-management systems. Access to a complete geometric definition of a part through solid modelling can reduce the boundaries between functional responsibilities within organizations. (Source: *Machine Design*, August 1995)

General round-up

The shape of the rapid prototyping industry is changing constantly as the number of users grows and the demand for faster, accurate and more reliable machines and materials increases. The rapid prototyping industry has undergone many interesting developments such as: (a) Popularization: rapid prototyping is beginning to enter the "mainstream". In some companies it is an integral part of their business; other companies still have to try it out while other may not have heard of it at all. Compared to CNC installations, most rapid prototyping units operate in service centres in both small and large companies, with the way in which the work is carried out being different to CNC; (b) Consolidation: At present the world-wide market is not large enough to support the present number of system manufacturers (16). Companies may merge, change ownership, or even disappear. A case in point is the recent acquisition by Stratasys (Minneapolis, MN, USA), of IBM's technology to heat and extrude thermoplastic materials to form models and prototype parts; (c) Publicly-owned corporations: in 1994, Stratasys offered its shares on the NASDAQ stock market (USA). Two other manufacturers in the USA are also publicly owned corporations (3D Systems and Soligen); (d) Cast metal parts: Projects involving cast metal are becoming more and more sophisticated. 3D Systems (Valencia, CA, USA) produced a 4-cylinder engine block casting, complete with cast-in water jackets and cored passageways for Mercedes-Benz (Stuttgart, Germany) in only five weeks, using their QuickCast process. Soligen's Parts Now unit (Northridge, CA, USA) produced a functional metal prototype of a complex engine component for Caterpillar in one week by using the company's proprietary Direct Shell Production Casting (DSPC), casting it in aluminium, heat treating it and delivering the part for installation. (Source: *Rapid Prototyping: State of the Industry*, 1994-95 Worldwide Progress Report, Wohlers Associates, OakRidge Business Park, 1511 River Oak Drive, Fort Collins, Colorado 80525, USA, April 1995)

C. RAPID PROTOTYPING AND CAD/CAM

Round-up of new developments

Makers of rapid prototyping equipment have recently displayed their equipment, which is more sophisticated, having new materials, making smoother, tougher parts at a lower cost. Several manufacturers are developing their first ceramic models which are aimed at making tools directly by methods such as inkjet printing, photocuring and sheet lamination. In CAD/CAM software, the latest updates are also more flexible and less expensive with several advances in mould-filling analysis.

Sanders Prototype Inc., Wilton, NH, USA, has produced an unusual new desk-top prototyper and plans to introduce a larger prototyper that prints ceramics. If successful, this would be the first to make highly accurate ceramic models of 0.003-inch layers. Cubital Ltd., Israel, is also developing a ceramic model for low-production tools. Its technology builds prototypes by spreading a layer of photosensitive polymer, curing it with UV light through a computer-generated mask, vacuuming off uncured resin and filling in the spaces with water-soluble wax.

Helisys Inc., Torrance, California, was recently awarded a US$ 3.5 million US Federal Advanced Research Projects Agency grant, with the University of Dayton Research Institute, to develop ceramic composite materials for its lamination technique using a carbon dioxide laser to cut sheets of plastic-coated butcher's paper and bond them into light, solid prototypes. However, paper blocks delaminate with moisture. The ceramic composite lamination will make more moisture-resistant patterns and low-production moulds.

Stratasys Inc., Eden Prairie, Minnesota, has introduced its first dual-material, rapid prototyping system, in which a new ABS filament makes the model and supports, and a second, low-temperature blue wax makes a thin release layer between the model and support, allowing the supports to break off cleanly. This technique melts and laminates a thermoplastic filament, making an outline pass with filament to obtain a smooth outer surface. It then builds layers back and forth with the filament.

Developments are still continuing in metal modelling where dimensional problems exist. DTM Corp., Austin, Texas, USA, sinters prototypes using laser light and is planning to have three trial sites in use soon so as to improve accuracy. They have added a new "fine nylon" material, 50-micron powder instead of 100 micron, which sinters into a smoother prototype. They plan to introduce two new thermoplastic modelling materials soon with hopefully even better finishes than fine nylon, at lower temperatures.

Imageware, Ann Arbor, Michigan, has developed a "Surfacer" reverse engineering program which accepts scan data representing complex 3-D dimensional objects, such as the human face. It absorbs the data, which may contain millions of measurement points, processes the data cloud into a meaningful CAD model and creates the CAD surface directly from the data cloud, according to the company. Apparently, the "interrogation tools" can be used to validate that a complex surface such as an air foil was built as designed.

Alias Research Inc., Toronto, Canada, has introduced enhancements to its software and reduced prices. Its StudioPaint Version 2.0 software can now run on the lowest entry-level Silicon Graphics workstations, Indy and Indigo 2, for reasonable prices. Cray Research Inc., Eagan, Minnesota, launched a new low-priced J90 series of supercomputers starting with the J916 which is a simulation server for small to medium-sized companies. The company's new CMLogic Version 2.0 analysis software, with new design-of-experiments and moulding simulation capabilities, runs exclusively on Cray's supercomputers. Exa Corp., Cambridge, Mass., USA, introduced its first beta software called "ExaResolute", a program for fluid flow analysis, claimed to be more accurate and faster than standard programs. The new software is based on different mathematics than conventional analysis. It takes a model that assumes a rectilinear grid filled with macro molecular particles which move and collide, giving a more accurate flow simulation than before. At present it is being tested for automotive air flow analysis, but can be used for applications such as injection mould filling, fuel injection and water cooling. Moldflow Pty. Ltd., Australia, has been carrying out research on a new flow analysis packing for coinjection moulding using a grant from the Australian government. Testing is expected in approximately two years.

AC Technology North America, Louisville, Kentucky, has introduced a new version of its C-MOLD analysis software for injection, gas-assist, coinjection, RIM, blow-moulding and thermoforming. It includes a new module entitled "Rapid Designer" with data on numerous resins, injection moulding machines, coolants and mould bases. AC Technology say it can be used to predict part cost, fill time, clamp force, injection pressure, cycle time and coolant requirements. The version for blow moulders also includes new animation so that engineers can simulate the parison inflating or being pre-blown and then blown. The image can then be manipulated by splitting the mould halves and angling the view to check a pinchoff. (Source: *Plastics World*, February 1995)

Speedier tools

Following recent software trends, design, analysis and manufacturing software now goes far beyond quickly making 2-D drawings. The more sharply focused software packages can tackle tougher technical problems. Manufacturing engineers can locate inlets, runners and insulation for greater productivity, especially when casting parts from unfamiliar alloys using casting analysis software. It may take a couple of days to set up and run the model, but dozens of various casting conditions can be examined in several days. Another trend is that developers are writing software that more easily swaps data with other packages. For instance, one software developer has integrated mechanical motion with stress analysis and optimization, operations that can together provide a potent engineering package and eliminate the time and potential errors of data exchange.

The most significant developments in these fields should be examined more closely. Solid models are quickly gaining acceptance as perhaps the best way in which to begin a design, even those which are predominantly 2-D such as sheet metal patterns. Analysis often starts with a solid model taken from an assembly of parts that was examined for interference. Several companies have developed packages that have pioneered modelling systems allowing the users to change models by typing in new dimensions or allowing several dimensions to be a function of a user-supplied value and updating these dimensions when that value changes. Such features are now almost commonplace. Developers are now looking for ways in which to quickly make model changes. An important development has been the emergence of capable entry-level packages. Many engineers only require the ability to step up to solid modelling from 2-D drawings but want to avoid the limitations of wire frame or surface only packages.

Mechanism analysis, or motion simulation software, is receiving a great deal of attention from developers and users. One developer reports that work has been carried out closely with several automotive companies which would allow automotive makers to assemble software components and dynamically model proposed vehicles. This method shows the way in which companies may have built prototypes using existing components, such as engines or transmissions, test it in an existing car and report on the findings. Today's scenario would be that an engineer could work from a menu of software modules representing existing components ranging from engines, suspensions, or new ratios in an existing transmission. The engineer could then pull software models for each component into a master menu and within a few hours "test drive" the "software car" and reveal any handicaps. After the necessary modifications, the R&D team would have a better idea of which existing components match the product specification. If no existing component matches the specifications, these are available for the company to approach suppliers with.

Software has also been made easier for the user. Some companies now offer 2-D analysis packages with a sophistication that was previously only available with expensive software set ups. It is now possible to have an on-screen control panel which lets users operate mechanisms. Graphs can be made automatically during operation and help analyse the reach of a unit and how much load it might safely pick up. One particular package includes friction and intermittent contact, phenomena which are frequently present in mechanisms but difficult to account for.

Optimizers—tools that find the best size, shape and thickness for a design's dimensions—have also progressed. An approach from one company can find the best location for support members after given constraints, loading and an allowable volume. Engineers might not necessarily pick the best spot, or may include redundant members when deciding where to locate the supports. Once the location and the type of beams are selected, a more traditional type of optimizer can select the most favourable dimension for the item such as material thickness or channel depth.

Design for manufacturing and assembly software can computerize time-cutting processes previously largely ignored. The software can allow the engineer to estimate part counts and costs in a given design. When using the software for the first time, users establish a benchmark by describing how parts in a product go together; the software gives the assembly time and cost, based on prevailing labour costs. One theory states that shortening assembly times and improved product reliability can come from reducing the number of parts. This is achieved by combining part functions, for instance, eliminating nuts and bolts in favour of snap fits. As the number of parts decreases, the complexity of those remaining can increase. This design can help the user to determine how best to manufacture the remaining parts.

Knowledge bases can store a wide range of information, such as rules, guidelines, tables and equations normally used to design products. The software can consult the rules and guidelines in far less time than a human would need when designing the part. This has largely been ignored in the part due to the time involved, cost and manpower to start with. However, once installed, considerable savings, both in time and money can be achieved.

Rapid prototyping has caught on because the models produced can give designers an instant insight into their creations. When handling such a model, designers can instantly know what needs to be changed—an on-screen model cannot provide such feedback. Emphasis has been placed on low-cost modellers and new methods for building investment casting patterns.

Manufacturing and processes are also experiencing more intense analysis scrutiny. It is known that complex geometry and the molten material make some moulds difficult to fill without generating scrap. Dimensional tolerances, shrinkage and hardness are a few more problems which casting shops face. Software can show how molten metal will flow into a die, how it will solidify and then look for problems such as a cold shot that freezes prematurely.

Other trends aimed at cutting production schedules include milling with multi-axis machines rather than three-axis mills. For example, an engine block can be fixtured several times on a three-axis mill; a five-axis machine can have rotary axes and a tilting head, allowing it to do more work with one tool and without repositioning the block.

In addition, one of the better applications of virtual-reality software checks toolpaths for accuracy. In a simulated removal process, users see the final part take shape, even seeing the fine scallops that a tool leaves.

Rapid manufacturing, possibly the next step after virtual reality and rapid prototyping, is beginning to take shape. Direct shell process casting is a recent process that jets an adhesive binding agent onto layers of casting ceramic, producing complex moulds and eventually finished parts in relatively short periods.

However, none of the above can be achieved without the proper equipment and training of the staff to operate it. Items such as a properly sized monitor, third-party software and up-to-date training all improve the design department's efficiency. (Source: *CAD/CAM Planning* 1995)

Partnership in virtual prototyping development

Five of the world's leading automobile manufacturers have joined forces with the world's leading mechanical-simulation software developer, Mechanical Dynamics Inc. (MDI), Ann Arbor, Michigan, USA, to gain strategic advantages from virtual prototyping, a way of using software to test-drive products via the computer. Strategic benefits will accrue for both partners: for the supplier as they confront new criteria for manufacturing success and for the software supplier as it creates customer value by working closer with key users. One of the goals is to amplify the strategic value of the software through the development of a version that can be easily customized to meet the individual requirements of each company. MDI is, in effect, integrating its customers into its R&D process so as to develop products of the greatest utility. It can also be seen as an example of a software company using the concept of mass production and conceptually modifying it to make it possible to give each customer a product with a customized content.

A further goal is the aim to make the mechanical-simulation tool widely available throughout the five organizations as an enterprise-wide solution and not keeping it in the engineering departments. The companies can make its mechanical-simulation tools something which various departments might use, including such functions as testing, design, development, research and management.

The software has revolutionized the design process for many firms in a wide range of industries. Telescoping the time factor is the big advantage of virtual prototyping, because the mechanical product and its subsystems can be built significantly faster on a computer—and it can certainly be tested faster. Consider how much time could be saved by letting the computer analyse how different transmissions affect vehicle behaviour as opposed to removing and installing different variations in an actual physical prototype. In addition, tests run on the computer are repeatable, and automobiles are not the only application for virtual prototyping. They are merely representative of the complex systems problems of many products.

When viewed as a whole, the new value set will go far beyond the usual benefits of this type of software—shorter product-development cycles, reduction in hardware prototypes, together with a greater ability to consider design alternatives. Both partners will gain a unique added value from this process. The automobile companies ensure the best possible solution of common prototyping problems, whilst the special efforts of the software provider tend to prevent competitors from making inroads.

It is envisaged that the software which will be developed will allow engineers to create computer models of vehicles with accurate representations of assemblies such as suspension, power-trains, engines and steering mechanisms, as well as traction, anti-lock braking and other control systems. The engineers will then be able to exercise the computer model under various road conditions to accurately predict handling characteristics, ride quality, vehicle safety and performance parameters in the early design stages. Custom interfaces will allow engineers and designers to create and exercise models with minimal training. (Source: *Industry Week*, May 1995)

Progress made in rapid prototyping

Rapid Prototyping enables the fast translation of CAD designs into cast metal prototypes. Progress in computer technologies has also resulted in speedy developments in this field. 3D Systems' QuickCast 1.1 version offers new possibilities in rapid prototyping processes. When used in investment casting the stereolithography process used can shorten the time from design to finished casting dramatically as it is no longer necessary to produce intermediate tools for wax patterns. In addition, the new version enables the production of patterns that are not solid but have an internal open honeycomb structure. These internal cavities enable the direct use of stereolithography parts as combustible patterns. Previously the usual solid SLA parts were only partially suitable for such applications as pressure increased during the combustion of the pattern possibly resulting in cracks in the ceramic mould shell. The honeycomb structure now achievable provides for the rapid and complete discharge of the residual liquid from the cavities. The remaining open cavity structure ensures the rapid discharge of the bases forming during combustion. The new software version also provides for a better surface quality through the option called "Thickskins" where three closing layers are automatically produced for the areas of the component facing upwards and downwards respectively.

The company says that this software was used to develop a complete aluminium engine block at Mercedes-Benz AG, the first time that an entire engine block was investment cast. Reportedly the process took five weeks, compared to 40-50 weeks which is typical for conventional methods. The method has also been successfully used by a medical products company which specializes in the production of orthopaedic components for rebuilding joints. The company, Johnson & Johnson Medical Products (Raynham, Mass., USA) was the first company to use the stereolithography process for product development in the medical sector. The process enables them to handle an order, perhaps requiring the production of a number of special components for knee implants, in the shortest possible time. Prior to this it was only possible to implement this with the assistance of a good toolmaker who would have had to individually modify standard series patterns by hand to suit the relevant special items. (Source: *Giesserei* 82 (1995), No. 17, p. 626)

The competitive edge through rapid prototyping

Rapid prototyping has the potential for significantly increasing the competitiveness of a manufacturing company. It is claimed that this technology can facilitate substantial reductions in product development times and improved product quality. There are two perceived and distinct roles for rapid prototyping: (1) as a three-dimensional plot of CAD data to prove the design intent and the quality of the information prior to using the data for manufacture; (2) as a means to create rapid master patterns for use in so-called soft tooling (rapid tooling) applications for niche market production.

When considering the time and cost implications, the first role is straightforward and well exploited in manufacturing sectors. There are well defined commercial reasons to prove data prior to committing to expensive and time-consuming tooling. The second role is less understood and contains significantly more variables. It is clear that manufacturing industry will not benefit from these techniques if it perceives rapid prototyping as a "high-tech" model-making system and its applications as a cheap short-cut.

The major benefit of rapid prototyping can be seen as time-saving. Any of the systems available will save a significant amount of time when integrated into the development cycle. However, how many businesses can quantify time as an overall cost and prefer to utilize tried and tested longer routes which have hidden overheads or perceived lower step incremental costs? Ultimately a 50-70 per cent time-saving should equate to earning revenue sooner, establishing a leading position in a market before the competition and improving the overall quality of the product for less cost.

It is important to consider rapid prototyping as a contributory factor in shortening the complete development process through to production. The greatest commercial advantage is only obtained when an organization is able to implement strategically the whole of the rapid prototyping and tooling process. This would entail a cultural change, firm commitment and drive from top-level management in any company. (Source: *Engineering*, November 1994)

D. RAPID PROTOTYPING AND STANDARDS

Changing manufacturing and its standards

It is said that rapid prototyping will do for manufacturing what the copy machine did for the office—revolutionize it. As a method for fabricating physical parts directly from computer aided design data, rapid prototyping has received the strongest support from the automotive industry, the medical device industry and the casting industry. However, the technology stretches far beyond these industries, and there is probably no industry that cannot benefit from it.

Being less expensive and faster than traditional mould-making methods, rapid processing processes employ a computer to design a part and then control a laser, extruder or other device to actually form the smaller shapes that comprise the whole part. Experience has shown that the technology has enormous advantages when making extremely complex parts.

Even with the euphoria around the rapid growth of the technology, industry has recognized the need for consensus standards which relate directly to rapid prototyping. It is planned to have a method of testing that allows a benchmark to be drawn against which the process and materials can be used. To this effect, an initial draft of a test method for tensile testing of rapid prototyping has recently been circulated to the members of the Subcommittee E28.16 on Rapid Prototyping of the American Society for Testing and Materials (ASTM). This test method covers the determination of the tensile properties of computer-directed, layer-by-layer-produced components when tested under defined conditions of pre-treatment, temperature, humidity, support removal and testing machine speed. Although materials testing is the main thrust of the subcommittee, there is also an amount of computer technology that needs to be addressed as well. The Subcommittee will focus its efforts on the development of standard test methods for determining the characteristics of parts fabricated using rapid prototyping techniques. The three main areas of concentration are: (1) mechanical properties; (2) morphological properties; and (3) materials properties. (Source: *ASTM Standardization News*, April 1995)

E. INTERNATIONAL/NATIONAL PROGRAMMES AND PROJECTS

Australia's experience—Queensland response

Due to its geographic situation Australia is insular at times, in that it can experience a lack of awareness of time-to-market pressures, minimal export awareness and a lack of in-house professional design and engineering capabilities. The Queensland Manufacturing Institute (QMI) was established in 1993 to meet the needs of small and medium-sized manufacturers. The concept behind the establishment of QMI was to complement planning aspects with practical, applied access to advanced design, development and manufacturing technologies. The focus of QMI is on rapid product development and advanced manufacturing technologies suitable for local manufacturers involving operation within a technology continuum ranging from emerging to mature technologies.

Research and development activity at QMI involves local, national and international partners. Its key innovation capabilities relate to accelerated product development for small and medium manufacturers; rapid development of short-run tooling related to plastic injection moulding, squeeze casting, die casting, and investment casting techniques; and medical applications of rapid prototyping techniques, including the manufacture of tailor-made prosthetic devices.

Experience at QMI has shown that the use of a simple methodology and a "toolbox" can facilitate a closer working relationship across the supply network, and ultimately facilitate better and more profitable products brought to the market in a speedier fashion. This toolbox addresses organizational issues, design and management techniques, and appropriate technologies that can be used by companies undertaking accelerated product development programmes. The approach of QMI and its clients combines the most appropriate subset of the toolbox to yield a pilot project for an improved product development process optimized for the needs of the smaller organization. QMI consultants found that technology in particular had an important role to play in breaking down barriers between departments and organizations in a country as large as Australia.

The structure of the manufacturing industry in Australia and a history of reliance on protection and primary industry mandates government intervention. QMI provides a new model for practical government assistance with advanced manufacturing technology and process improvement for small and medium manufacturers.

For more information contact: Ian Haynes, Queensland Manufacturing Institute, PO Box 4012, Eight Mile Plains, Brisbane 4113, Queensland, Australia. (Source: *Rapid News*, Vol. 3, No. 2, 1995)

Japan — hardware costs drop

The Japanese Ministry of International Trade and Industry (MITI) has recently begun a four-year US$ 840 million project to support the development of a rapid prototyping system that small and medium-sized firms can afford. As rapid prototyping systems in Japan are extremely expensive, cost is a major issue there. Another problem that Japanese rapid prototype makers face is that they must import key components, including lasers and galvanometer mirrors. The MITI project may well address these areas as well.

Rapid prototyping systems available in Japan are similar to those in the USA. The leading Japanese vendor is Computer Modeling and Engineering Technology Inc. (CMET) which was established as a joint venture by Mitsubishi Corp., NTT Data Communication Systems and Asahi Denka Kogyo. The technique employed by CMET is similar to that of 3D Systems Inc., Valencia, California, whereby a laser is used to cure photosensitive polymer in the required shape. The technique is called "SOUP" (solid object ultraviolet laser plotter) and originates from research at the Nagoya Municipal Industrial Research Institute. The company is currently working on improvements in several areas. Epoxy-based resins are a popular means of getting more accurate models and to reduce shrinkage and distortion. The latest CMET applicator takes less than 30 seconds to traverse its build plane. The company foresees that more than 1,000 stereolithography systems will be installed in Japan by the year 2000. It plans to focus its efforts on the Asian region, having already exported 300 systems to various countries in this area. The company feels that Europe is too remote for marketing purposes and that it is locked out of the USA, both by the lead held by 3D Systems, and by the uncertainty over licensing and patents. The company cannot be sure of all the details of patents held by 3D Systems, because the USA patent system does not have disclosure. The outcome of the Japan-USA Framework Talks Agreement, under which the USA should introduce disclosure in exchange for a Japanese commitment to hasten patent processing is uncertain—it may or may not make the 3D Systems patent portfolio transparent enough for CMET to assess whether the USA is free of legal land mines. CMET holds around 50 patents in Japan, and several in the USA. 3D Systems has roughly the same number of peripheral patents in Japan and world-wide. CMET will consider exporting to the USA when these patent procedures are resolved.

Another company, Sony Corp., has models which require post-curing. This company believes that its system has advantages over the SOUP system. For example, the entire resin tank can rise to bring the liquid closer to the laser light source, boosting accuracy, with the laser spot size being adjustable as well. The latest machine from Sony can also adjust to different parameters for each layer thus helping prevent shrinkage and distortion; an applicator has been angled to counteract distortion caused by surface tension.

The third-largest supplier of rapid prototyping machines, Teijin Seiki, uses stereolithography machines using urethane acrylate photopolymers and can handle a model envelope of 500 mm, on a side. These machines are mainly used in the electronics and automotive industries.

Matsushita Electric Industrial Co. is one of the biggest users of rapid prototyping in Japan. It has two SOUP systems in the die and mould department at its Manufacturing Systems Engineering Center in Osaka. They plan to acquire more machines when the budget allows it. Rapid prototyping is mainly used here in developing fans the annual production is 22 million in 200 varieties. The technique provides considerable savings for them, as the typical prototype test cycle for a fan must be repeated 10 or 20 times. Matsushita say that rapid prototyping has cut design development from four weeks to ten days and cut the cost by more than half. The company also gives rapid prototyping the credit for cutting the time needed to get the product on the market. (Source: *Machine Design*, November 1994)

Long-term approach to RP in Japan

Organizations in Japan are channelling talent and research funds into the development and application of rapid prototyping technologies. Japan has, in particular, taken a long-term approach to understanding market needs and requirements while refining stereolithography.

Even though there is a choice of 14 different rapid prototyping systems available in Japan, less than 120 systems are in operation in the country. The limited use of CAD solid modelling has been a limiting factor in the low volume of sales; however, solid modelling is beginning to take off in Japan. This will play a critical role in the growth of rapid prototyping in the country, as a digital model is needed before a rapid prototyped part can be produced. If a CAD model has to be produced for the purpose of rapid prototyping, the result can be that rapid prototyping is too costly.

Companies in Japan are developing and refining rapid prototyping technologies quickly. Much of what is available meets, or even exceeds, the capabilities of American or European technologies. Many companies are, at present, concentrating on enhancing the capabilities of their technologies, with particular emphasis on accuracy. They see a need to refine their processes over time, working closely with their customers to define market needs and requirements. (Source: *Rapid Prototyping: State of the Industry*, 1994-95 Worldwide Progress Report, Wohlers Associates, OakRidge Business Park, 1511 River Oak Drive, Fort Collins, Colorado 80525, USA)

The European experience in rapid prototyping

Even though rapid prototyping was pioneered in the USA, European countries are catching on fast to this technology. Over the past couple of years several German applied research centres and a number of companies have been collaborating to develop this technology. As a result, some of the most advanced work is now appearing in Germany.

The most popular form of rapid prototyping in Germany is stereolithography, which builds models by repeatedly applying, and then curing with a laser, thin layers of photoreactive polymer. One of the leading research institutes, the Fraunhofer Institute in Aachen, is researching on improving dimensional tolerances in large models. The Frauhhofer Institute is also focusing on so-called fused-deposition modelling, using polymer and wax to form layers of a 3-D model. Schneider Prototyping GmbH in Bad Kreuznach say they are able to produce models up to 100 mm long with a 0.001 mm tolerance. Service bureaux are appearing rapidly all over the country. A growing number of European companies are beginning to field their own versions of rapid prototyping technology. For instance Electro Optical Systems GmbH, Munich, offers two versions of a laser-based stereolithography system. Sparax AB, Sweden, is marketing a system which constructs models by bonding sheets of polystyrene. Laser D3 in Nancy, France, has developed a high-speed laser-based stereolithography.

In manufacturing industry, perhaps the most notable users of rapid prototyping are found in the automotive industry with the Rover Group, UK, being the largest, closely followed by BMW in Germany. BMW AG used rapid prototyping to reduce its product design cycle for a particular car component from 12 to three weeks. However, engineers had to invest more time in generating high-quality data for the prototype model by ensuring that their CAD descriptions contained no voids or undefined surfaces, otherwise the software used would become confused and generate faulty data requiring manual corrections. (Source: *Machine Design*, October 1994)

UK Rapid Prototyping and Manufacturing Association

This is a newly established non-profit association dedicated to assisting manufacturing companies, research and technology organizations in the UK in making advances in rapid prototyping. In particular the association aims at: (a) providing a forum for the exchange of experience-based information on accuracy, surface finish and operating costs of each technique in rapid prototyping; (b) fostering the formation of consortia of non-competing companies to develop techniques; and (c) making available information from overseas centres of excellence on best practice. (Source: *Machinery and Production Engineering*, 2 June 1995)

The International Rapid Prototyping Association (IRPA), UK

The Rapid Prototyping and Tooling Club (RP&T), which was managed by the Warwick Manufacturing Group, Coventry, UK, and now in its third year of existence, is transforming itself into the International Rapid Prototyping Association (IRPA). Membership of the club has grown beyond expectation in terms of level of interest and diversification of membership, numbering almost 12,000 world-wide. Through its concentration on technology transfer, the Club established a reputation and level of service to industry that was hard to beat.

The decision to transform the Club into the IRPA was taken as the point had been reached where it was considered appropriate to have an industry-led organization to continue and develop the level of support expected from the members. A committee has been established to manage the Club during the transition period. The initial work of this committee has been to establish the direction of the IRPA, a constitution and suitable electoral and management procedures. The formal transformation took place in June 1995. All commitments of the original RP&T Club will be honoured by the IRPA and they look to expand the activities to reflect the professionalism and drive of the IRPA.

People interested in joining the IRPA should contact: Tim Plunkett, Chairman, IRPA, c/o Formation Engineering Services Ltd., Unit A3, Spinnaker House, Hempstead Lane, Gloucester GL2 6YA, UK. (Source: *Rapid News*, Vol. 3, No. 2, 1995)

Round-up of European research programmes

Most European programmes concentrate on the application of existing technologies and on educational needs and opportunities as opposed to developing new system technologies. This does not mean that no developments of new systems take place in Europe (of which Germany leads in developing systems), research in Europe generally takes place through combined consortia activities, due largely to the funding available from the

European Union. The following European programmes are of particular interest:

CARP: The Computer Aided Rapid Prototyping (CARP) is a three-year consortium supported by Europe's EUREKA programme. It focuses on integrating elements of CAD, CAE, RP, interfaces, working practices and model development.

EARP: The European Action on Rapid Prototyping (EARP) is a three-year project formed to serve as a central forum for information exchange and cooperation and to establish new R&D areas in Europe. At the beginning of 1995, the consortium comprised 35 active partners from universities, research centres and private industry working on 17 programmes. These included the organization of conferences and exhibitions focusing on advances in medical modelling using rapid prototyping.

INSTANTCAM: This project was to improve and increase the use of rapid prototyping technology through a partnership of 11 organizations from five countries.

NOR-SLA: This was a Nordic industrial research project entitled Machining Data for Production of Stereolithography Models. Its basic objectives were to perform research to determine how SLA models could be produced with the best possible dimensional accuracy and surface finish at the lowest possible cost. This project has spurred a further, larger project within the Nordic region on Layer Manufacturing, involving 40 companies and institutes.

Fraunhofer Society: Some impressive work is being carried out at the various Fraunhofer Institutes in Germany. The centre-point of their work on rapid prototyping is the WISA project which aims to: (1) develop 3-D digitizing technologies for reverse engineering; (2) address software and data transfer issues using STEP; and (3) develop rapid prototyping technologies for the production of metallic prototype parts and tools. (Source: *Rapid Prototyping: State of the Industry*, 1994-95 Worldwide Progress Report, Wohlers Associates, OakRidge Business Park, 1511 River Oak Drive, Fort Collins, Colorado 80525, USA, April 1995)

F. MARKETING

IBM to enter the rapid prototyping market?

IBM may soon enter the rapid prototyping market with technology developed at its T. J. Watson Research Laboratory. It recently showed an engineering model of an apparatus that builds up prototypes from thin layers of extruded thermoplastic material. The company says it is presently evaluating different options for commercializing its rapid prototyping technology, either through partnership with another company, or bringing its machines onto the market alone. The machines are apparently small enough to fit on a desktop and have a reasonably low price label.

The IBM technology employs an innovative pump-and-nozzle assembly to extrude the plastic material and can handle materials of widely varying viscosities allowing the machine to build models using a variety of thermoplastic raw materials. This assembly allows fast changeovers between modelling materials, though switching by purging the pump and adjusting the nozzle and takes approximately five minutes, according to IBM. The materials used consist of three types: one that is adequate to mould material for investment casts, another more flexible elastomer analogous to synthetic rubber, and a third that is rigid enough to be machined. They plan to employ the same technology to accommodate additional materials such as ceramics. The machine has even been used to produce prototypes from chocolate!

IBM has also written software that automatically plans supporting structures for prototypes under construction. Special supports are needed when models contain overhanging features; without these, the overhangs would sag while the modelling material hardened. IBM say that the software can recognize and compensate for problems commonly found in stereolithography format files, such as holes in defined surfaces and similar geometric anomalies. (Source: *Machine Design*, April 1994)

Rapid progress in rapid prototyping

Rapid prototyping technology has now evolved beyond producing models to assist in the visualization of the "touchy-feely" parts. Techniques have progressed so rapidly that master patterns for castings and metal moulds are now being made in days rather than months as with conventional prototyping. Initial capital costs for rapid prototyping are still relatively high; even those prices are dropping slowly. It is not always necessary to make a large investment immediately. Success can be gained when traditional tool- and pattern-makers become computer literate and operate the new systems. It is anticipated that, in the future, desktop systems the size of a laser printer will be available. (Source: *Engineering*, February 1994)

The state of the RP industry—progress report

1994 was a pivotal year for the rapid prototyping industry. It was a most progressive year with more systems being sold in 1994 than in 1992 and 1993 combined. Many user companies purchased second and third systems with tens of thousands of rapid prototyping jobs being processed. Service providers experienced a productive year, after-market products and services began to appear. However, some manufacturers still offer their systems at prices that many CAD/CAM users find hard to accept. Notwithstanding this fact, rapid prototyping is becoming a critical part of everyday business in many companies, particularly in the USA.

It is estimated that revenue from sales and services grew by 99.7 per cent in 1994 with unit sales growing by 84 per cent; the milestone of 1,000 installed units was also surpassed in 1994.

The world leader continues to be 3D Systems Inc., Valencia, California, with an estimated share of 50 per cent of all systems installed world-wide. Japanese companies lag behind with an estimated 14 per cent share of the world-wide base of installations. European countries are rapidly developing systems which are becoming widely accepted.

The number of service bureaux has grown to 155, according to CAD/CAM Publishing Inc. (San Diego, California). This is an increase of 47.6 per cent. These bureaux have expanded their operations by adding more machines and people as demand for their services increase.

Wohlers Associates (USA) expect rapid prototyping to improve and become more cost effective over the next decade, similar to the evolution of personal computers. They say that rapid prototyping is a technology which is changing the way products are brought to market, which does not necessarily mean that it is easy to integrate and justify. With adequate research, planning and cooperation, any company can be among the number of success stories in this fast-paced industry. (Source: *Rapid Prototyping*: State of the Industry, 1994-1995 Worldwide Progress Report, Terry Wohlers/Wohlers Associates, April 1995)

System	Advantages	Limitations
Stereolithography	Quickcast™ system permits successful and economic sacrificial patterns. Quickcast™ system gives higher accuracy and better structural integrity of models. Very wide range of application experience—excellent user groups. Best surface finish of currently available techniques. Most parts can now be "right first time".	Expensive raw materials initially, but model material costs comparable to other systems. Expensive annual maintenance charges. Limited range of materials (photosensitive resins) Support structures needed but these are automatically supplied from purpose-written software. Care needed with environmentally hazardous solvents used to clean up.
Selective laser sintering	Range of model materials. Wax models can be invested directly. Polycarbonate models after surface treating with wax can be used as sacri-ficial patterns. Lower cost of raw materials than stereolithography or solider systems.	Wax models need 12-hour cooling cycle on the machine. Wax models very fragile. Recycled unsintered powders need careful sieving to avoid "ball-ups" and "furrowing" when new layer of powder is laid down. Support structures can be necessary, especially for complex, overhanging features of wax models. Learning curve necessary with most new parts.
Laminated object manufacture (LOM)	Relatively lower capital cost system. Low cost of raw materials. Finished models resemble wood—popular with traditional model makers.	Inherent fire risk. Most models require subsequent hand working to improve surface finish. Inherent difficulties with undercuts and re-entrant features. Waste material can be difficult to remove.
Fused deposition modelling	Lower initial cost of system. Low cost of materials. Can be operated in office environment. Highly reliable machines. Short build time for thin-wall parts.	Poor surface finish but can be improved by hand working. Support systems necessary for complex overhanging features.
Solid ground curing (solider)	High capacity of model building chamber. When chamber is used to full capacity, can be most economic rapid prototyping technique. Complex models possible, including ready assembled multi-component products.	Large, heavy, noisy, expensive system. Prone to breakdowns. Requires constant manning. High consumption of expensive raw materials. Models cannot be used as sacrificial patterns for conventional investment casting.
3-D printing systems	Direct route to ceramic shell production for investment casting. Wide range of materials possible soon (in principle, any material available in powder form). Potential for low-cost machinery and low-cost model materials. Potential for purpose-designed computer-controlled microstructure.	Commercial machines not yet available. Shells very fragile, especially in thin sections. Removal of powder from narrow cavities can be difficult. Ceramic powder needs to be stabilized with mist of water droplets.

G. RECENT EVENTS

CONFERENCES AND EXHIBITIONS

Rapid Prototyping and Manufacturing Conference and Exposition

This was held from 2 to 4 May 1995 at the Hyatt Regency in Dearborn, Michigan, USA. The theme was "1995 is the Year of Rapid Tooling". More than 40 new conference presentations focused on the latest trends in prototyping applications. There were over 85 exhibitors presenting a wide array of equipment, technology and information. Conference sessions included the following themes:

- How can users integrate rapid prototyping applications into existing CAD/CAM programmes?
- How are companies translating CAD data?
- What are the advantages of using a table-top milling machine to rapidly prototype a part?
- What are the benefits of reverse engineering to rapid prototyping?

Conference participants had the opportunity to tour one of six manufacturing plants, where they saw rapid prototyping machines in action and how the equipment was integrated into the design shops. Tutorials were held which covered the fundamentals of rapid prototyping, rapid tooling from rapid prototyping, an introduction to Standards for the Exchange of Product Data and concurrent engineering.

The Conference was sponsored by the Society of Manufacturing Engineers and the Rapid Prototyping Association (USA), amongst others. Further information can be obtained from: Society of Manufacturing Engineers, Box 930, Dearborn, MI 48121, USA. (Source: *Machine Design*, April 1995)

Manufacturing Week '95—UK

This exhibition was held from 10 to 12 October 1995 at the National Exhibition Centre, Birmingham, UK, and is the UK's largest engineering show. Over 550 companies exhibited at the show, representing 15 areas of technology, including: advanced manufacturing, control and systems engineering, drives, motors and controls, fastening and joining, instrumentations, materials, pneumatics and hydraulics, rapid prototyping and sensors and systems. Within the umbrella of this show, smaller exhibitions were held including a robot village, and Plant 95, which was a dedicated event for plant and factory engineers. Inspex 95 is the UK's leading metrology and inspection event and Weldex was for cutting and welding.

The Rapid Prototyping Exhibition was held at which the Warwick Manufacturing Group, Coventry, UK, hosted an information centre where visitors could obtain free advice on the benefits and implications of rapid prototyping.

Seminars were held focusing on how to achieve manufacturing excellence through the successful implementation of best practices and leading-edge technology. Plenary sessions were interspersed with workshops offering more detailed information.

For more information contact: Manufacturing Week '95, P.O. Box 18, Barking, Essex, IG11 0SA, UK. (Source: *Engineering*, October 1995, and *Rapid News*, Vol. 3, No. 2, 1995)

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

UNIDO

MAILING LIST FOR PUBLICATIONS

If you would like to receive any of the following series in future, please completethe list below and return to the address indicated below.

INDUSTRIAL TECHNOLOGY MONITORS

- ☐ Genetic Engineering and Biotechnology Monitor
- ☐ Microelectronics Monitor
- ☐ Advances In Materials Technology Monitor
- ☐ Marine Industrial Technology Monitor
- ☐ High-Tech Spin-Offs Monitor

ADVANCED TECHNOLOGY TRENDS SERIES

- ☐ Advanced Materials Technology Series No. 1
  (Advanced Materials in High Technology and World Class Manufacturing)
- ☐ Environmentally Sound Management of Biotechnology
  (The Task Managers' Report on Chapter 16 of Agenda 21)

FAMILY NAME & GIVEN NAMES	
TITLE OR POSITION	
ORGANIZATION	
STREET AND/OR P.O. BOX NO.	
CITY AND POSTAL CODE	
COUNTRY & TEL./FAX NO.	

Please describe briefly the work and responsibilities of your company/institute/organization, including the number of people employed:

Please send to:

UNIDO
Industrial Technology Monitor
Industrial Information Section
P.O. Box 300
Vienna International Centre
Vienna A-1400
Austria

Previous issues of the Advances in Materials Technology Monitor covered the subjects listed below. Whilst we hold an extremely limited stock of back numbers, these are generally the most recent issues. The Monitors are all available on microfiche, at a cost of US$2 each from:

United Nations Officer at Geneva
Distribution and Sales Section
Palais des Nations
CH-1211 Geneva 10
Switzerland

Issue No. 1	Steel
Issue No. 2	New Ceramics
Issue No. 3	Fibre Optics
Issue No. 4	Powder Metallurgy
Issue No. 5	Composites
Issue No. 6	Plastics
Issue No. 7	Aluminium Alloys
Issue No 8	Materials Testing and Quality Control
Issue No. 9	Solar Cell Materials
Issue No. 10	Space Related Materials
Issue No. 11	High Temperature Superconductive Materials
Issue No 12	Materials for Cutting Tools
Issue No 13	Materials for Packaging, Storage and Transportation
Issue No 14	Industrial Sensors
Issue No. 15	Non-Destructive Testing
Issue No. 16	Materials Developments in Selected Countries
Issue No. 17	Metal-Matrix Composites
Issue No. 18	Plastics Recycling
Issue No. 19/20	Advanced Materials Technology:CAD/CAM Applications
Issue No. 21	New Materials Technology and CIM
Issue No 22	Powder Metallurgy
Issue No. 23	High Temperature Ceramics
Issue No. 24/25	Surface Treatment Technologies
Issue No. 26	Reinforced Plastics
Issue No. 27/28	Industrial Applications of Simulation
Issue No. 29	Modern Ferrite Technologies and Products
Issue No. 30	Russian Space Programmes and Advanced Materials Development
Issue No. 31	Solar Cells and their Industrial Applications
Issue No. 32	Metallic Superconductors and their Industrial Applications
Issue No. 33	Materials Testing and Evaluation
Issue No 34	Biodegradable Polymers
Vol.1, No. 1, 1994	Sensors and their Industrial Applications
Vol.1, No. 2, 1994	Biomaterials and their Industrial Applications
Vol.1, No. 3, 1994	Materials for Severe Environments
Vol.1, No. 4, 1994	Laser Materials and Industrial Applications of Lasers
Vol.2, No. 1, 1995	Rapid Prototyping and New Materials