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Rapid Prototyping and Manufacturing Technology: Principle, Representative Technics, Applications, and Development Trends*

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Abstract: The rapid prototyping and manufacturing technology (RPM), is an integration of many different disciplines. It is based on an advanced dispersed-accumulated forming principle and originated from 1980s. It generates an entity by first forming a series of layers according to the dispersed section information of the digital model, and then piling the formed layers sequentially together. It is capable of forming parts with complicated structures and non-homogeneous materials. Traditional RPM techniques are mainly used as prototypes in product invention process, such as stereolithography, three-dimensional printing, laminated object manufacturing, and fused deposition modeling. Later, with the progress of material and enabling technology, many new RPM techniques emerged out and have been already applied in the fields such as rapid tooling/moulding, direct formed usable part, nano-/micro-RPM, and biomanufacturing. This high flexible digital manufacturing method has a likely ability to become an almighty forming technology.

Key words: rapid prototyping; rapid manufacturing; dispersed-accumulated forming; rapid tooling; rapid moulding; biomanufacturing

Introduction

From thousands of years of humankind history, we can see that most of our civilization was founded on the base of forming/shaping technology, and actually the history of humankind civilization has been propelled by the evolvement of forming/shaping technology. And we can conclude that our beautiful future will benefit a lot from the frontier field of modern forming technology which we are now devoting in, such as rapid prototyping and manufacturing (RPM) and its derivative techniques.

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Modern forming/shaping science is the science that researches on orderly organizing the materials into a three-dimensional (3-D) part with determined shape and functions. According to the method for organizing the materials, it can be divided into four basic categories:

(1) **Removal forming** an ancient method to form a part by orderly removing redundant materials from primal rough model, such as traditional lathing, milling, planing, drilling, grinding, laser cutting, and electrical discharge machining (EDM). It is now the most important processing method.

(2) **Forced forming** an ancient method to form a part by imposing external constraints like a cavity or exerting pressures onto the material stuff, such as traditional forging, casting, and powder metallurgy. It is mostly used for roughcast while some like precision casting and precision forging are aslo for direct

end-forming of net or near net shape.

(3) **Dispersed-accumulated forming** (as shown in Fig. 1) a novel method to form a part by first dispersing the materials (gas, liquid or solid state) into points or lines, and then piling up them into layers and bodies.

(4) **Growth forming** the forming process of all natural organism bodies (plants, animals, etc), mostly relied on the proliferation and self-assembly process of materials like cells; for example, the spiral fractal geometry of a trumpet shell is developed from its natural growth process. It is now the most complicated and highest forming level.

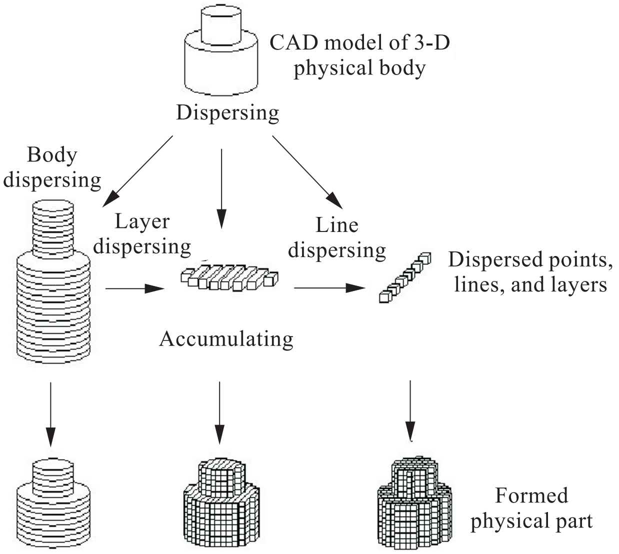

Fig. 1 Illustration for dispersed-accumulated forming

Since the late of 20th century, the original removal and forced forming methods have been hard to meet all demands in increasingly competitive manufacturing market of globalized economy, and a personalized and flexible forming method has been required. On the other side, computer-aided design (CAD) technology, laser technology, numerical control technology, and material technology have been rapidly developed.

Thus in this background, a novel interdisciplinary subject of rapid RPM technology came out[1], which is the general term for all technologies based on the dispersed-accumulated forming principle. It disperses the process of forming a complicated 3-D physical part into forming a series of two-dimensional layers, and then piles up the layers together. This is a typical order-reduced and material-increased forming technology. It can complete forming a 3-D entity with an arbitrary complicated structure directly controlled by its digital CAD model.

This dispersed-accumulated forming principle has been mentioned long ago. In 1892's US patent (No. 473901), Blanther proposed a method to constitute a topographic map by layered manufacturing, and after 1950s hundreds of RPM-related patents were proposed. However, the fundamental developments came out in 1980s. The most known is that Charles W Hull was inspired by ultraviolet (UV) light-curing resin and proposed the stereolithography (SL) technology (US patent, No. 4575330) in 1986, based on which 3D System Corporation produced the first modern rapid prototyping machine (SLA-250) in 1988. Since then, tens of RPM technics have emerged out, and there were 274 patents registered in US during 1986-1998 period. As issued in Terry Wohlers's annual RPM report[2], it has already achieved a lot in many fields. And the GARPA (global alliance of rapid prototyping associations) was set up and have been promoting this technology into much wider and deeper applications.

1 Principle

1.1 Dispersed-accumulated forming

The discrete methodology means the method/theory that aims to analyze, process, and achieve the general or precise solutions of complicated things and systems by dispersing them into limited or unlimited simple things or sub-systems. For example, the process of calculous is first differential of integer into units, then integral of units into integer. Actually most of objects are composed of discrete units. It is obvious that breaking an object down into limited or unlimited units, would make the processing of complex issues much more simple.

The dispersed-accumulated forming is actually the application of discrete methodology in the forming/shaping field. For example, when a pyramid is to be built, firstly how many pieces of stones, their shapes, their exact locations, and orders to be piled should be pre-designed, which is the dispersing process; then these stones are produced and are orderly piled them up into a pyramid, which is the accumulating process.

In the process of dispersed-accumulated forming, the manufacturing of a 3-D part is transformed into manufacturing of a series of simple units. In some sense the unit itself has broken through the traditional manufacturing concept: it can be either a material droplet, or a cell, or even a protein molecule.

In a word, we can get the paths and the conditions for later accumulating through the dispersing process while through the accumulating process to pile up dispersed materials to form a 3-D entity. This type of forming principle is an advanced concept. It is the integration of discrete methodology and manufacturing science. The ultimate evolvement of discrete is digital, and the ultimate evolvement of this forming method is digital manufacturing.

1.2 Digital manufacturing

Usually the manufacturing process is composed of information process and physical process. The application of computer technology in manufacturing industry has already realized the digital description of information process and strengthened the combination between information process and physical process. This resulted in numerical controlled (NC) design and manufacturing such as computer numerical control (CNC) processing technology, flexible manufacturing systems (FMS) technology, computer-integrated manufacturing system (CIMS) technology, and digital simulation technology.

However, as illustrated in Fig. 2, the NC design and manufacturing only achieves digital information process and numerical controlling of tools in the forming process. The transfer of forming materials in the physical process is still completely passive, not numerical controlled. Therefore, from this point of view, this approach is still a type of analog forming, or numerical controlled analog forming.

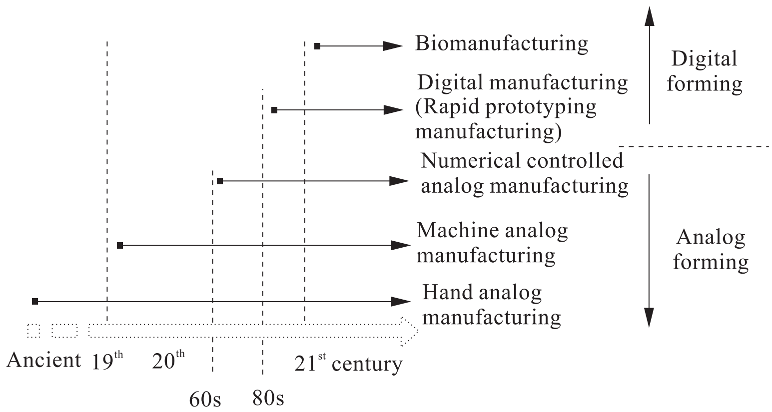

Fig. 2 Illustration of digital manufacturing and anolog manufacturing

Comparatively, RPM technology not only realizes the digital information process, but also the digital physical process. In RPM, the material-transferring process is based on the piling ability of materials. Controlled by digital information, forming materials are added on-demand, and gradually step-by-step accumulated in forming area to shape up the final part which further enhances the flexibility of the forming process.

Thus, from the material-transferring features in the forming process, RPM can be regarded as a complete digital forming technology. The data processing is very important in RPM process. Figure 3 illustrates the flow chart of this process. In the data processing, layered process and algorithm is the kernel for all rapid prototyping and manufacturing techniques.

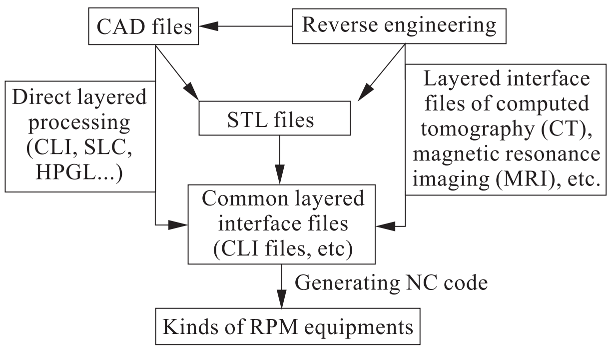

Fig. 3 Data processing in RPM process

1.3 RPM family

RPM is a great family, in which each member is defined with a special name according to its special function and application of the formed pieces such as rapid prototyping (RP), rapid manufacturing, rapid tooling (RT)[3], rapid moulding (RM), and biomanufacturing (BM)[4,5].

RP is the first emerging technology in the RPM family. Its formed pieces are mainly used for the evaluation of the structure, assembly, and color of the designed models, as well as for the customer quoted prices, academic discussions, and *in vitro* models of prosthetic organs.

When the RP-formed pieces contain other functions (performances) besides the above-mentioned functions such as special mechanical properties, electromagnetic properties, and biological properties, they can be applied into many other fields such as forming mould, direct parts manufacturing in aerospace, automotive, household appliances fields, and bio-medicines. And thus they derive many technical branches in RPM such as rapid manufacturing, rapid tooling, rapid moulding, and biomanufacturing. Although these branches are in dynamic development, some would be eliminated while some would emerge out, it should be emphasized that all of them are based on the same dispersed-accumulated forming principle.

There are also many other names for RPM technology in the international community, all are defined from different points of view to emphasize a particular aspect of its features such as: (1) free forming fabrication, or solid freeform fabrication, which means that this forming method needs no special fixtures and moulds; (2) dispersed-accumulated manufacturing, which denotes its fundamental guiding principle; (3) layered manufacturing, which emphasizes the importance of layers in piling up process; (4) material increase manufacturing, which denotes the accumulating forming process; (5) direct CAD manufacturing, which denotes that it is directly controlled by CAD models; (6) instant manufacturing, which emphasizes its rapid response; and (7) e-manufacturing. Among all of the features, the most important is that this technology is fast and flexible in whole forming process which makes its common name as rapid prototyping and manufacturing.

2 Representative Technics

Since 1986, more than ten main technics of RPM[6] technology were developed such as stereolithography (SL), laminated object manufacturing (LOM), selective laser sintering (SLS), selective laser melting (SLM), fused deposition modeling (FDM), ink jet printing (IJP), 3-D printing (3DP), patternless casting manufacturing (PCM)[7], and electron beam selective melting (EBSM). There are many classifications for these technics. According to the enabling technology, there are two categories: (1) one is based on the high-energy beam (laser, electron beam) and (2) the other is based on the droplet jetting or slurry extrusion.

2.1 Technics enabled by high-energy beam

The representative technics are SL, LOM, and SLS. SL is based on the photopolymerization of liquid photosensitive resins induced by UV radiation. This type of facility usually contains a liquid basin filled with liquid photosensitive resins, a mobile elevated workbench with a porous board, UV laser implements (He-Cd, argon or solid state laser, power range from dozens to hundreds of mW, wavelength range from 320 to 370 nm), and a scanning system (optical mirror array reflects the laser beam and focuses it onto the liquid surface, and performs the *X*-*Y* directional scanning movement). As issued above, Charles W Hull got the US patent of SL in 1986. And in 1988, 3D System Corporation in US introduced the commercial SLA-250, which is the world's first RPM machine. The other similar machines are SOUP (CMET, Japan), Stereos (EOS, Germany), and Auro (Yinhua, China).

The forming materials for SL mainly contain free radical light-cured resin, cation light-cured resin, and mixed-type light-cured resin. The resins are composed of further polymerisable prepolymer, active monomer, photoinitiator, and other auxiliary components. Radiated by UV light, the photoinitiator would transit from ground state to excited state, then generate active free radical, triggering the polymerization curing reaction between prepolymers and active monomers. The mixed-type light-cured resin is now mainly used. It has low polymerization volume shrinkage and even has a small expansion, and can be designed to be no-contraction polymer. It can provide polymer systems with short induction periods and stable polymerization rates. It could also overcome the shortcomings that the free radicals would quickly be inactive and the polymerization course would quickly stop after the disappearance of laser radiation.

This kind of technics is of high precision. It can produce very fine parts with good plastic-like surface quality. However, the support material is needed. And it is of high cost for the photopolymerizable resin and laser system.

LOM uses laser (or knife) to cut patterns on thin layers, then piles the layers together. The basic structure of the machine contains a paper feeding and rolling implement, a heat-presser, altimeter sensors, *X*-*Y* scanning system, mobile elevated workbench, and sometimes a CO_2 laser system (power: 50 W). This technics was first invented by Michael Feygin in 1986. And the commercial machines were later launched by Helisys Corporation in US. The other similar machines are SAHP (Kira, Japan), SSM (Yinhua, China), and ZIPPY (Kinergy, Singapore).

The forming materials are usually thin sheets like papers and polymer films. And there are three common problems involved: the sheets, the hot-melt adhesives, and coating technology. The performance of sheet should be ensured of certain tensile strength (preventing it from being pulled off in forming process), good soakage ability (for good coating), hydrophobic (not easy to absorb water), little shrinkage (no deformation due to loss of water), easy to be polished (for smooth surface), and good stability (for long-term store). The main ingredients of hot-melt adhesives are EVA resins combined with tackifier, wax, and antioxidants. And it should be with proper melting viscosity, mobility, contraction, adhesion, infiltration, and thermal decomposition temperature. The coating technology includes uniform coating and non-uniform coating. The former uses a simple device of slit-scraper while the latter includes striped style and particles style, which can reduce the stress concentration but are more expensive.

This kind of technics is suitable for large pieces of solid part with high accuracy, needs no additional support in forming process. The prototype pieces are with a hardwood texture. But the post-processing is usually time-consuming, and produces more waste.

SLS forms parts by piling up layers of laser-sintering metal or non-metallic powder. This forming machine basically contains a laser implement (CO_2 laser or YAG laser with a general near-infrared band wavelength of 1.06 μm, and a power of 50-200 W), an optical system (used to focus and orientate the laser beam), a function generator and an industrial personal computer (controlling laser beam to scan in the *X*-*Y* plane), a hopper, and a spreading system (loading powder and spreading the powder surface to flat). This technics was first developed in 1989 by CR Dechard in Texas University at Austin. And later, it was commercialized as Sinterstation by DTM Corporation in US. The other similar is EOSint (EOS, Germany).

The forming materials include wax powder, metal powder, polystyrene (PS), engineering plastics (ABS), polycarbonate (PC), nylon (PA), coated sand, and coated ceramic powder. In recent years, composite powder with a diameter of 50-125 μm is often used. The effect of laser on powder material has two stages. First one is the absorption and reflection of the powder surface. In this stage the absorption of laser energy is related with the laser wavelength and the powder surface state. Second one is the heat transferring in powder material. In this stage the powder heating and cooling process are very soon, and the material parameters vary rapidly with the rise of temperature, what is a very complicated and unstable thermal conduction process. Thus, the powder material should be of good thermoplastic ability, a certain degree of thermal conductivity, and adequate bond strength.

This technics can directly form parts without additional support. And it has an extensive material resource. However, the accuracy is not very high.

2.2 Technics enabled by jetting/extrusion

The representatives are FDM, ink jet printing (IJP), and 3DP.

FDM is one of the most popular RPM technics. It forms a part by extruding melting viscous slurry-like materials out and deposited them on the base plane or previous formed part. Then, the material conglutinates to adjacent material and cools in open air. The nozzle is very important in FDM machine. It is responsible for melting materials and extruding them out precisely on-demand. It was first successfully developed by Dr. Scott Crump in 1988. And Stratasys Corporation in US introduced the first commercial FDM series equipments. The other similars are MEM series (Yinhua, China).

This technics usually uses filamentous thermoplastic materials such as ABS, wax, and nylon. The material is heated and melted in the nozzle, and then extruded out for accumulating forming.

IJP builds part by shooting/jetting material droplet on-demand from piezoelectric ink-jet printing nozzles. And high forming velocity can be achieved by a liner array of ink-jet nozzles. The representative commercial machines are Actua (3D System, US) and

ModelMaker (Sanders, US).

The forming materials are mainly wax and wax-like thermoplastic polymers with a medium strength between wax and technical thermoplastics.

3DP uses ink-jet printing nozzles to jet binder droplets onto solid powder surface. After one layer is formed, the next layer of powder is spreaded on the former layer. The forming velocity can be accelerated by providing a linear nozzle array. This technics was first invented by Prof. Sachs in MIT, then commercialized by Soligen Corporation in US in the name of DSPC (direct shell production casting) used for manufacturing of ceramic shells and cores for casting. The other similar machines are 3DP (Extruhone, US), and 3DP (Z-corp, US).

This technics needs no additional support, and can form an extensive range of materials that can be conglutinated by available binders such as ceramics with binder, metals with binder, and polymers with binder.

3 Features and Traditional Difficulties

Observed from Fig. 4, the novel forming method of RPM technology has a series of important features:

(1) The process is directly controlled by digital CAD models. The process of CAD and the process of computer-aided manufacturing (CAM) were integrated together; it needs the least or no human intervene. It is an automated process of forming.

(2) The process is with a high degree of flexibility. It can build arbitrary complicated 3-D physical parts using a general machine without special fixtures and tools.

(3) The material forming process is integrated with the information process. It is especially suitable for forming a part with non-homogeneous materials and gradient function or porosity.

(4) Compared with other forming methods, this technology is much more rapid in the process from the design to a formed part, and the cost has no relation with the manufacturing quantities.

(5) RPM is a highly integrated technology. It benefits a lot from the other emerging high technologies such as CAD, NC, and material technology.

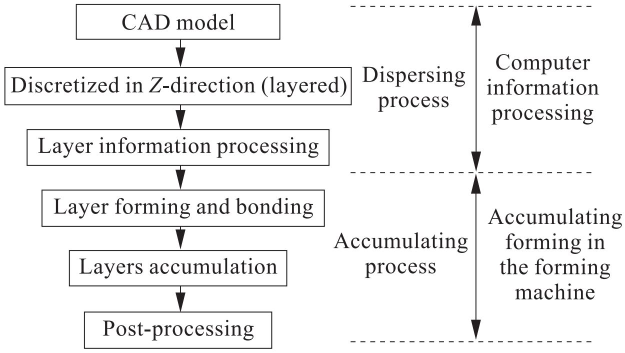

Fig. 4 Flow chart of RPM process

As described above, in the early developmental stage of RPM, it was mainly applied as a forming method of product prototypes, in the invention process such as design test and assembly, known as rapid prototyping. And yet it had to compete with the virtual reality (VR) and high speed milling (HSM) technology. However, due to the distinct principle of dispersed-accumulated forming process, it can deal with non-homogeneous materials and complicated structures, what makes it more potential in further development and applications.

And the constraints that traditional RP technics faced were developmental levels of available forming materials, forming precision, forming velocity, and manufacturing cost:

(1) **The residual stress** The dispersed-accumulated forming process is always accompanied with phase-change and temperature-varying process of materials, the residual stress is difficult to eliminate, and the deformation and warpage after forming is easy to occur. Measures such as pre-/post- warming may reduce it in some extent, but not totally satisfied.

(2) **The limited types of available materials** RPM technology is greatly dependent on the properties of the material itself. The material should not only be suitable for dispersed-accumulated forming process and postprocessing, but also have certain mechanical strength and some functions after forming. At present, the most popular materials for RPM are mainly resin, wax, certain engineered plastic, and paper. However, there was no mature technics for the widely used metal, ceramic, polymer, and biomaterial.

(3) **The insufficient forming precision** The precision is restrained by the unit scale, known as the step effect determined by present insufficient level of material dispersing. And the low precision needs

postprocessing to compensate the step effect which further consumes time and reduces the flexibility and rapidity.

(4) **The conflict between precision and forming velocity** This is the conflict between information and physical process. The forming time is inversely proportional to the cube of dispersed unit scale. Therefore, if the unit scale slightly decreases, the used time would significantly increases. One available method is to use the nozzle array.

(5) **The high manufacturing cost** The RPM is an integration of high technologies. The technical cost is high. At present, it is used for single or low mass production, the average fixed cost is high. And the special prepared materials are usually much more expensive than other available industrial materials. For example, the Viper Si2 SL-equipment of 3D System Corporation in 2001 costed 180 000 USD; and its special resin was 200-250 USD/kg.

4 Applications and New Progress

After two decades of development, RPM have stepped into the maturity. Many new technics emerged out, and a lot of measures were developed to promote the RPM. Though it was originally used as an auxiliary method for developing the new product in the process of design, test, and assembly, now it can directly form functional entities like metal parts. It is also applied in nano-/mirco- fabrication and biomanufacturing as a powerful forming method.

4.1 Curved-surface layered manufacturing

The layered error for curved surface, known as step effect, is the principle error of RPM technology. It prominently affects the precision and surface quality especially when the angle between the horizontal plane and the surface is small. To decrease this error, besides reducing the layered height, which is restrained by the materials and technics, optimizing the direction of forming is another acceptable method, in which process it is needed to be layered along curved surfaces instead of being easily layered along parallel planes.

Curved-surface-layered manufacturing forms a part along a series of layered curved surfaces. The layered algorithm of constructing the layered curved surfaces, including the key frames and transition frames from a CAD model, is one key technology. The other is the forming control technology. First one is the controlling of the nozzle moving track and the nozzle pose in forming process. To form curved surface, it is upgraded from traditional 2-axis plane scanning to 3-axis 3-D scanning, and the pose of nozzle should be controlled to avoid the formed part from damage. Second one is the material delivery control. The on-demand material should be determined according to the real-time nozzle parameters to eliminate over-stack and lack-stack.

This technology can be only fitted for certain RPM technics like FDM. The material preparation process of technics such as SL, LOM, and 3DP, produces a plane material layer for the next step processing, making them impossible for manufacturing along curved surfaces. The forming material of FDM is added on-demand, and the extrusion velocity and axis-moving velocity can be controlled at real time, what makes it suitable for curved-surface layered forming. Actually, our team had used a MEM-300-II (Yinhua, China) to complete the first curved-surface layered prototype.

Besides the curved-surface layered algorithm, there are also some other new technologies in CAD model dispersing process such as rapid layered algorithm of STL, direct layered algorithm of CAD model, and self-adaptive layered algorithm. With these improvement, the errors in layered process can be greatly eliminated, the information process efficiency can be improved, and the integration between front CAD and end RPM can be further upgraded.

4.2 Machines for concept prototype

The RPM was brought out as a method to manufacture concept prototypes, what may be used in processes such as design, test, and assembly. After 2 decades of progress, many types of commercial machines in this field have been developed. All of these equipments are similar in some common features as follows: (1) rapid forming velocity; (2) able of dealing with multi-kind materials (for continuous-gradient-colored products); (3) able to be controlled by PC through standard communicating interfaces; (4) small like a desktop device; (5) low manufacturing cost, low price; (6) green, pollution-free, and noise-free in manufacturing. And the representative commercialized equipments are as follows:

(1) Z400 and Z406 (Z-Corp, US). Both are based on

jetting to bind powder materials. Single-colored Z400 has an array of 128 nozzles (from CANON, Japan) and a layer precision from 0.075 mm to 0.02 mm, while Z406 is multi-colored, has 4 basic-colored binders that can be composed of 6 million kinds of colors, and each basic color has an array of 400 nozzles (from HP, US).

(2) Quadra (Object, Israel). This machine integrates 3-D ink-jetting and light-curing process to photopolymerize jetted resins in time by the UV light. It has a vertical 60-mm array of 1536 nozzle heads, which can form a layer in 2-12 s and complete a one-inch high prototype in less an hour. The system is of high efficiency, and the layer precision can be as low as 0.02 mm.

(3) 3-D 300C (Solidimension, Israel). It is based on LOM, and uses knives to cut plastic films and conglutinate them by adhesives, thus the deformation is very small. The equipment only weighs 31 kg, and is one of the cheapest concept machines at present.

(4) Tier Print 3D (Yinhua, China). This is a desktop equipment, compact, is easily controlled, and needs no training. It uses ABS plastic, cheap, of high strength and certain elasticity. The support is intelligent, can be easily removed.

(5) Thermojet (3D System, US). It is based on jetting fused wax materials, has an array of 350 nozzles and an acceptable high forming precision.

(6) Prodigy (Stratasys, US). It is based on FDM, has two kinds of materials respectively for entity and support. The layer precision can be chosen as 0.175 mm, 0.25 mm or 0.33 mm.

4.3 Rapid tooling and rapid moulding

Rapid tooling and rapid moulding, an important part of RPM, a new mould design and manufacturing system, is widely used in the injection molding and metal casting industries. It refers to directly create moulds with different types of RPM techniques, and then attain required mechanical properties, dimensional accuracy, and surface quality with necessary postprocessing and machining. It can rapidly get a finish mould and has a distinct advantage in those moulds that need complex flow system for cooling, compared with other methods.

(1) Rapid wood-pattern-free sand mould such as PCM, DSPC, general RP systems (GS), and *Z* cast direct metal casting. PCM was originated in Tsinghua University, China. It completes a mould by jetting resin or other binders onto refractory material layers such as sand and ceramic powder. It was industrialized by Fenghua in Foshan, China.

(2) Methods based on powder metallurgy such as 3-D Keltool, launched by 3D System Corporation in US. It fills resin-mixing tool steel powder in the middle silicone mould reversed from an SLA prototype, then bakes it to remove the binder. A 30% porous mould will be gotten, which would be finally infiltrated with copper and simply machined. The precision can be up to 0.04 mm. It can sustain a pressure of 20-25 kPa and a temperature of 650℃.

(3) Methods based on the deposition method such as rapid solidification process, originated in Idaho National Engineering and Environmental Laboratory, US. It deposits a fixed thickness layer of alloy powder, ceramic, and polymer onto prototypes by certain deposition technics like metal sputtering. The surface roughness *Ra* can be 0.0735 mm, and the deposition rate can be 227 kg/h.

(4) Direct mould by SL. 3-D System directly formed the accurate clear epoxy solid injection mould with SL and special material. However, this kind of mould is short-lived, and the complexity is limited. SOUP (CMET, Japan) has a similar process.

(5) Electroforming mould. It coats a conductive layer onto the prototype, and then places it in the electroforming tank to attain a metal shell at room temperature, and sinters it to remove the prototype. Finally, after casting low melting point alloy, or resin-mixing aluminum between the mould casing and outer metal shell, the electroforming mould is completed.

(6) Others such as quick casting (3D System, US), baking ceramic-coated SL prototype to get ceramic casting shell; and unbaked ceramic mould tooling (Tsinghua Univ, China), reversing a ceramic mould from the middle silicone mould reversed from RPM prototype.

4.4 Machines for finish usable part

The concept prototypes and moulds can not exert full power of RPM, actually, it can be used in producing single or small batch of finish usable parts. These parts are of high precision, can be fitted with certain requirements of strength, stiffness, and other functions. And the forming efficiency should be acceptably high.

3D System Corporation in US, cooperated with DSM Somos Corporation in US, developed a new type of photopolymer resin with which the formed fan could be used in the wind tunnel test. Stratasys Corporation developed an FDM Titan equipment, which could use polycarbonate (PC) and polyphenylsulfone (PPSF) to make parts with high impact strength, good thermal and chemical stability, its made belt pulley could replace the damaged aluminum belt pulley in production line with normal operation.

As for the most important finish metal part, there are kinds of novel techniques as follows:

(1) Methods based on laser beam cladding/sintering such as laser engineered netshaping (LENS) (Optomec Design, US), direct metal deposition (POM Inc, US), laser additive manufacturing (Aero Met, US), direct metal selective laser sintering (3D System, US, F&S/MCP, Germany; and EOS, Germany), and selective laser melting (Fraunhofer Institute, Germany; MCP, Germany; TRUMPF, Germany; Leuven University, Belgium; and Liverpool University, UK). Taking LENS as example, it uses Nd-YAG laser to sinter metal powder with the protection of inert gas, thus it can make aluminum-alloy, titanium-alloy, tungsten-alloy semi-refined rough parts while the precision surpasses traditional closed-die forging, and the internal quality is over the integral forging.

(2) Methods based on electron beam melting such as electron beam melting (Arcam, Sweden) and EBSM (Tsinghua University, China). EBSM uses high-energy electron beam to melt metal powders, and by controlling of electromagnetic field, the beam can be regulated to determined site. With this equipment, parts with good mechanical strength have been made of stainless steel powder, and titanium powder.

(3) Methods based on laser-induced chemical deposition such as rapid prototyping of laser-induced chemical vapor deposition (Connecticut University, US) and rapid prototyping of laser-induced chemical liquid deposition. The former deposits metal material from the photochemical, thermochemical, photodecomposition, and thermaldecomposition reactions of gas induced by laser while the latter is from liquid.

4.5 Nano-/mirco-RPM

Traditional nano-/micro- processing techniques are restrained in forming abnormal microstructures such as with high depth-width ratio. While RPM may surpass this shackle. For example, based on the two-photon absorption and light-cured manufacturing, researchers in Osaka University attained a 120-nm microstructure. And a nano bull of 10 μm long and 7 μm high was made.

Some researchers in University of Illinois jetted the polymer mixtures into solution through a micro pen to create 3-D network structures with 0.5-5.0 μm diameter of filaments. And the Mirkin team at Northwestern University first proposed the dip-pen nanolithography (DPN) to achieve direct high-precision patterns. It uses the atomic force microscope (AFM) probe to coat self assembly monolayer (SAM) material onto the sample surface. The line width is as small as 10-15 nm, and the space distance can be 5 nm.

The RP center in Nanjing University of Aeronautics and Astronautics, China also developed an electro-deposition technique simliar to electroforming. And some parts were made of nano materials such as Ni, Cu, Co, Ni-Fe, Ni-P, and Ni-SiC. The grain size is 30-50 nm.

4.6 Biomanufacturing based on RPM

Biomanufacturing (BM), an interdisciplinary field of RPM and tissue engineering[8], aims to manufacture the alternatives for the defect human tissues or organs. Flexible RPM is feasible for manufacturing accurate artificial nonliving alternatives such as prototypes of needed tissues/organs. Moreover, natural organs are composed of different kinds of cells and extracellular matrix materials (ECMs), and the cells exist in ECMs space with a specific distribution and orientation. Therefore, if RPM can directly manipulate the cells and ECMs as some forming materials, the living alternatives with physiological functions could be made.

According to the RPM application levels, there are three stages of BM. The first stage is the organ prosthesis manufacturing, which can be divided into two classes according to whether the prosthesis would be implanted. *In vitro* prosthesis is not implanted, needs no biocompatibility, is made of non-biological materials using traditional RPM techniques, and generally used in assistant diagnosis, surgical planning, patient communication, and assisted surgery. While *in vivo* prosthesis is implanted such as the prosthesises of stainless steel/titanium alloy bone, ear cartilage[9], skull, and larynx, mostly it is made of bioinert materials with improved RPM techniques to avoid immuno rejection and inflammation.

The second stage is indirect cell assembling, which refers to a two-step method to fabricate tissues/organs. First, the biomaterial scaffold is made by a certain improved RPM technique; secondly, the cells with growth factors are seeded on the scaffold and cultured to proliferate and migrate until the functional tissues/organs are regenerated. For example, 3DP was used by Griffith L. G. and the others to form osteochondral scaffolds[10] with gradient material and porosity. We developed a low-temperature deposition manufacturing (LDM) to form three levels of continuous gradient porous scaffolds with PLLA, PLGA, TCP, collagen, and gelatin[11,12]. Other improved techniques such as FDM, SL, and SLS were also used. Some new techniques such as 3-D Bioplotting[13], desktop rapid prototyping robotic dispensing system, and precision extruding deposition have been developed.

The third stage is direct cell assembling, which refers to directly operating cells, biomaterials, growth factors, and depositing them at specific spatial site according to the designed digital model derived from the anatomic model of an organ or tissue. Later, the products will be cultured/trained to help cells proliferate, migrate, orientate in certain patterns, and contact with each other, and the construct may finally develop into certain tissue with special physiological mechanical properties. Except for that Boland T took a novel attempt to encapsule living cells in SL process, all the others are brand new developed techqiues such as cell printing (organ printing/bioprinting)[14], 3-D direct controlled cell assembling[15,16], 3-D bioassembly (3-D BAT), multi-nozzle deposition system, laser-guided direct writing (LGDW), and 3-D photopatteming. For example, the 3-D direct controlled cell assembling was developed by our team in 2003. With this, kinds of thermo-reversible biomaterials such as gelatin, alginate, chitosan, and fibrin can be mixed with cells, and extruded into low-temperature forming chamber to fabricate living construct.

5 Development Trends

5.1 Technical improvement

Most of traditional mechanical parts are usually made of homogeneous materials, and with relatively simple extrinsic shapes and intrinsic structures. Some parts of non-homogeneous materials are usually made through several steps such as deposition and electroforming. However, the dispersed-accumulated forming feature of RPM is very suitable for directly forming parts with different kinds of non-homogeneous materials. And it is potential to create complicated parts with gradient material and structure. With the continuous technical progress, it is sure that this kind of parts made by RPM would be widely used in some day.

5.2 Rapid mass production

This is developed for the mass customization such as the mass production of dental appliance by Aligh Inc, and the mass production of hearing aid in the ear (ITE) by Phonak Group and Simens Hearing Instruments. The Aligh Inc. used SL technics to produce invisible dental bracketless appliances according to the personalized features of a certain patient. They had produced 3 million appliances by Dec. 2002. And the ITE was also designed and manufactured according to the feature of each client. This type of customized mass production will be an important application of RPM in the future.

5.3 Going deep into nano-/micro-RPM

The nano-/micro- technology is one of the hottest spots in 21st century. It is believed that many important applicable techniques will derive from this field. As an advanced forming method, RPM is very competent in manufacturing complicated 3-D nano-/micro- structures that other traditional methods can not afford. It will play an important role in nano-/micro- structures such as micro electronic mechanical system (MEMS), biochip, nano circuit, molecule motor, sensitive chemical test system, and high-throughput drug screening systems.

5.4 Application in direct metal forming

Metal remains the main material in industry, and the direct metal forming based on RPM is one of the most concerned problems in science and industry field. At the conference in Frankfurt, Germany in Dec. 2000, Terry Wohlers, the president of GARPA, Dr. Roger Spielman from Boeing, and Dr. Philip Dickens from

De Montfort University all agreed that it was the time to emphasize rapid part manufacturing.

At present, direct accumulated forming parts made of ferrous metals, non-ferrous metals, and other high-temperature alloys are still difficult in application. However, the rapid metal forming techniques will become the mainstream of the progressive laser netshaping technics such as high-power laser sintering, laser coaxial powder feeding, and 3-D welding. And there are already 12 manufacturers that are able to provide direct metal forming equipments.

This powerful technique can directly manufacture special-property and functional metal parts with such as titanium, tungsten, and high-temperature alloy. It can be applied in aerospace, national defense, and medical fields. For example, functional precious metal pieces such as impeller blades and the turbine disk can be directly formed with special alloys, high-temperature alloys or other advanced materials. The Boeing has already tried to use RPM to manufacture parts for space station and F18 warplanes. These parts such as in satellites are mostly of composite materials, have freeform surface, and are produced in small batch, which are especially for RPM.

5.5 Application in biomanufacturing

It is known that there is a great worldwide demand for kinds of artificial alternatives. BM based on RPM is a very useful technique in this field.

The design and manufacturing of prosthesis are already mature. There were lots of reported clinical surgeries about orthopedic prostheses, artificial joints, and craniofacial prosthesis. We succeeded in artificial hip arthroplasty repair and implanted skull prosthesis repair. Polyurethane (PU) ear prosthesis was also proved to be potential in clinic.

Based on indirect cell assembling, now biomanufacturing of structural tissues such as skin, bone, cartilage, large vessel, and muscle tendon have made great progress. Some of them have been commercialized. With LDM technics, 15 mm segmental rabbit radio bone defect, 20 mm segmental dog radio bone defect, and rabbit articular cartilage defect had been successfully repaired. Based on a developed RP dissolving-depositing technology, we successfully created multi-branch, multi-layered vascular scaffolds and the results of dog femoral vein defect repair were good.

In recent years, technology to construct internal organs based on direct cell assembling became hot. Our team aimed to fabricate hepatic tissue analogs and got some results. And this technique can also be used in some other fields such as pharmacology testing model and drug delivery system. For example, our team established an energy metabolic system model which is potential in high-content drug screening field[17].

5.6 Service-oriented manufacturing

The final aim of RPM is to freely manufacture any part that someone desires. There should be no shackles from the thinking models to finish entity prototypes or parts. The majority of human should be relieved from how to manufacture and devote themselves in thinking, new ideas, and the pursuit of new knowledge. From this viewpoint, RMP in future should be a service-oriented technique.

And there may be three types of RPM equipments: (1) the developing equipment for small and medium enterprises in rapid product invention; it is desktop-like, easily controlled, of low cost and high reliability; (2) special equipment for specified field such as military industry, aeronautics & astronautics, and important national projects. This kind of equipment is used for small batch of parts that need extreme properties such as high precision and high mechanical strength, usually made of special alloy, special ceramic, and polymers; (3) general forming equipments in manufacturing center for high-efficient and high-quality production.

The third type may be the mainstream in the future. It will be a high integration of customized production, internet-based production, and manufacturing centers. The manufacturing center provides services of original equipment manufacture (OEM) and original design manufacture (ODM). Because of the high cost of RPM forming equipments, this type of center can greatly cut the fixed cost and be splendidly professional in providing the most proper forming measures.

When the clients have a demand of certain medium/small quantity of products, they can freely design the structures and define the materials, and then transfer the scheme to manufacturing center by network, and finally fetch the products there. The network can also facilitate the clients in design and communicating essential information face-to-face in time. For example, several doctors can diagnose the patient on internet who needs teeth orthopaedics, and communicate together to determine the therapeutic treatment, then design a series of invisible dental bracketless appliances and transfer them to appointed manufacturing center; finally, the formed appliances will be directly or indirectly delivered to the patient.

6 Conclusions

During two-decade development, the RPM has been recognized as an advanced and flexible manufacturing method. Many techniques were developed while more techniques are emerging out. The forming precision and velocity have been continuously improved, the equipment and material cost continue to be reduced, and more available common materials continue to be developed. Besides the traditional prototype application in product invention process, it has a tremendous potential use in fields such as rapid moulding, rapid part/metal manufacturing, nano-/micro-RPM, and bio-manufacturing. It is believed that with the progress of the related technical disciplines, RPM will be more and more likely to transform into the so-called almighty manufacturing technology.

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