INNOVATIVE EDUCATION IN ADDITIVE MANUFACTURING IN CHINA

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Abstract

Beginning in 1992, China began to conduct research on additive manufacturing (AM) (i.e., rapid prototyping manufacturing or solid freeform fabrication). These studies included three main areas: processes, equipment, and applications in different fields. At the same time, various educational initiatives in AM were also begun.

Regarding the first area, a number of courses related to AM are now being offered in universities and colleges, and not just in those that have already developed research programs on AM, such as Tsinghua University, Xi'an Jiaotong University, Huazhong University of Science and Technology, and South China University of Technology, as well as some higher vocational schools. Owing to the orientation of these colleges and schools, their focus tends to be on the practical applicability of the courses they offer.

In addition to the lectures they offer, all of these universities and colleges are equipped with a laboratory or resources for experiments, and have brought in equipment on which students can practice operating software (3D CAD. etc.) and make prototypes of their own design. Along with the development of AM research in China, the proportion of equipment in Chinese production is increasing as well. Moreover, these courses offer lectures, employ Ph.D. students as teaching assistants for undergraduate or junior college students, and also offer training related to creative design and manufacturing for postgraduates. This training has produced good results, in that it requires postgraduates to combine what they have learnt during lectures with their own research.

In addition, associations and companies have played an important role in the development of AM in China by interacting with society and offering a number of seminars and workshops. There are many companies that offer courses for people with specific interests, and courses for engineers and technicians have created a boom in AM in China’s automobile industry. A number of associations and companies have even jointly organized design competitions in vocational schools. When students participate in these competitions they become familiar with the advanced technology of AM, an experience that is very important for their future work.

Key Words: Additive Manufacturing, Rapid Prototyping Manufacturing, Solid Freeform Fabrication, Innovative Education

1. Introduction

Beginning in 1992, China began to conduct research on additive manufacturing (AM) (i.e., rapid prototyping manufacturing (RPM) or solid freeform fabrication (SFF)). These studies included three main areas: processes, equipment, and applications in different fields. At the same time, various educational initiatives in AM were also begun[1-7].

Three new concepts of advanced manufacturing, namely AM, RPM, and SFF (which have similar meanings), are attracting increasing attention not just in advanced industrial countries, but also in many developing countries such as China. Many scientists and experts have driven these advanced technologies into the 21st century. Universities and institutes throughout China are introducing this new technology of AM (or RPM or SFF) into their research and education systems. Methods, processes, and systems for AM are also developing rapidly. Owing to the growth of the economy and society, there are definite requirements for this type of development. AM is having a profound impact on the way models, prototype parts, and machine parts are being produced, and there are many AM companies in China. The recent growth of this practice is developing into an intriguing market opportunity, as AM may even become one of the most significant fields of growth in China in decades.

The information process of AM technology is shown in Fig. 1. The key information process is the data channel. To control this channel, the application of computer technology in AM has helped realize a digital description of the information process and has strengthened the coordination between the information process and physical process. The physical process of AM technology involves layer-by-layer manufacturing. In this regard, Fig. 2 shows the uniform systems of data, energy, and materials that act on one another so that the physical structure of a part is obtained[8].

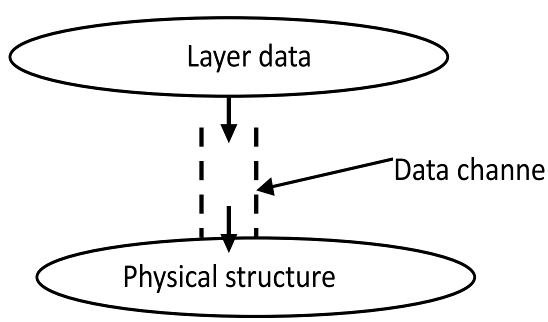


Fig. 1 Information process of AM technology

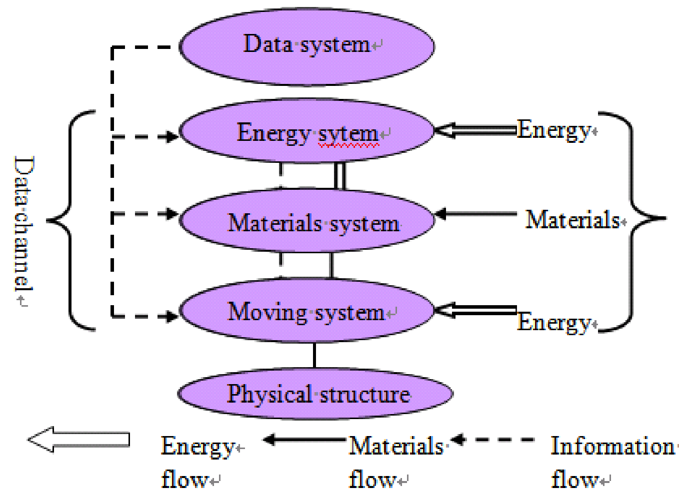


Fig. 2 Relationship among the three flows

In the modern science of forming, scientists conduct research on the orderly organization of materials into three-dimensional (3D) parts that have pre-determined shapes and functions (entirely or in part). There are four basic categories of forming activity that are based on the methods used for organizing materials (Fig. 3): (1) forming based upon removal, which includes traditional technologies such as cutting, lathing, milling, planing, drilling, and grinding; (2) forced forming, which includes casting, forging, and welding; (3) additive forming, a novel method in which a part is formed by first dispersing the materials into points or lines in a computer and then piling them into layers and bodies; and (4) forming based on growth, which is the process by which all living organisms are formed, and the process that relies primarily upon the proliferation and self-assembly process of bio-materials and cells. This fourth mode of forming is addressed in the section of this paper that discusses bio-manufacturing. There is, however, a BM_1 method that is considered to be part of the additive mode of forming. Here, we refer to bio-manufacturing without cells as BM_1, whereas BM_2 indicates that the cells participate in the forming process, so that the growth forming process is inevitable.

Innovative education in AM plays an important role in engineering and technological education in China. It follows that the progress that is made in education could then increase such educational innovation. The Department of Mechanical Engineering in Tsinghua, China focuses a great deal of attention on the adoption of new resource materials, the adaptation of courseware, active learning, student engagement, and educational technology, among other areas of interest. The transformation of undergraduate education in this department has produced a vast number of products and processes since its inception. The school's courses in AM technologies have fostered innovation nationwide, and they have also helped improve the overall quality of science, technology, engineering, mathematics, and calculative engineering. More often than not, though, these innovations remain local, in that they are developed and used only in the initial education of all postgraduate students.

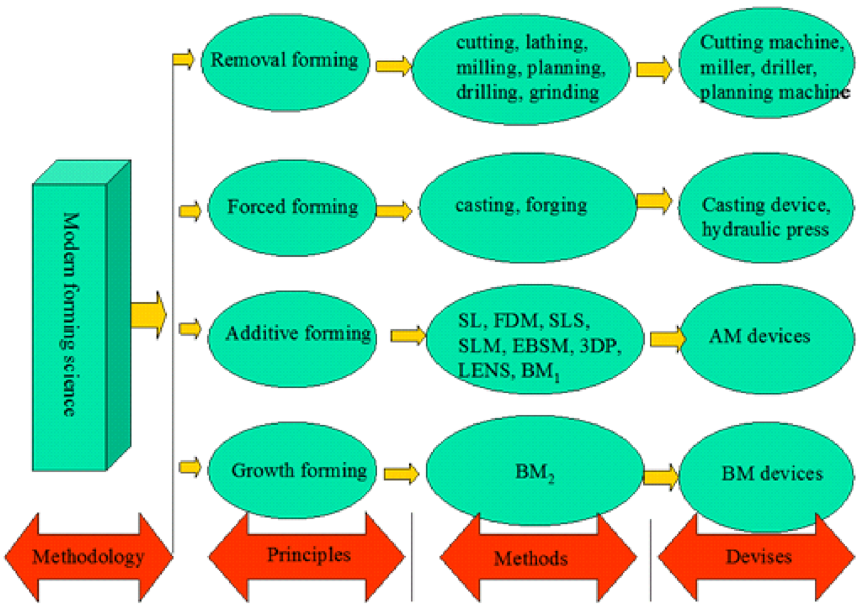


Fig. 3 Schematic of formation science and engineering

<u>2.Courses in universities and colleges</u>

Since 1998, courses in AM technology have been supported by the Educational Department of Tsinghua University. A multitude of individual projects have been adopted, some of which have gone on to be widely disseminated, whereas many others have only been used locally by the research group. A number of universities and institutes have begun to establish these new types of courses because this process typically recognizes and disseminates fairly large-scale innovations. The result is that most innovations have been developed through such new courses in different universities and institutes.

First, a number of courses related to AM are being offered in universities and colleges, and not just those that have already developed research programs on AM, such as Tsinghua University, Xi'an Jiaotong University, Huazhong University of Science and Technology, and South China University of Technology, as well as a number of higher vocational schools. There are currently more than 100 universities and colleges in China that offer courses in AM technologies and related courses. Owing to the orientation of these colleges and schools, their focus tends to be on the practical applicability of the courses they offer[9].

Moreover, these courses offer lectures, employ Ph.D. students as teaching assistants for undergraduate or junior college students, and also offer postgraduate training related to creative design and manufacturing. This training has produced good results, in that it requires postgraduates to combine what they have learnt during lectures with their own research.

2.1 Innovative education for courses in AM technologies

The research and education related to AM technologies focuses on an understanding of their principles and methods. The principal investigators of these technologies in China are currently considering the importance of their educational innovations, and what might be the barriers to their dissemination in different universities and colleges. Both the nature of these innovations and how changes in the new courses can be implemented need to be discussed in detail in the educational community. Recent research has produced a proliferation of changes and new innovations, but with little or no concern for their efficacy or importance. Some of the possible reasons why this field of education undergoes a process of fairly continual change could also be discussed.

1. A new type of course is a practical one that involves a strong dimension of practice. Many of these innovations have come from or spread among other institutes, companies, and/or universities, but few of these have seemed to experience continual changes.

2. There has been some discussion of why educational innovations apparently come and go, in both national and international conferences in China, as well as worldwide. In China, we have held five national and three international conferences from 1995 to 2011, and much useful related information could be learned from them. Such useful information also comes from associations and committees, major vendors, relevant journals, and local service bureaus, among other sources.

3. It is most important that there be teaching training for new courses in universities and colleges. We need more and more teachers who have greater practical experience. With regard to the issue of innovation, there seem to be two areas where teacher preparation could better meet teachers' long-term needs. One area regards teacher training that has a greater focus on measurable effects in their instruction. The other is the need for more knowledge on the theory and principles that describe how learning occurs, and how instruction influences learning.

4. Teachers also play a critical role in the fact that innovations seem sporadic, without stable development, in part as a result of their training. Innovators are often eager to try new programs and seem to thrive on the risks involved. Innovations come and go in part because they are never widely or permanently implemented in university or college programs.

5. Administration for a new and innovative course involves advanced degrees in education as well as training. Administrators play a key role in introducing innovation, as well as changes in the curriculum that become necessary. A long-term administrator may do this, but the teachers usually outlast the administrator in a given institution, and a lesser degree of progress is

the result.

2.2 Characteristics of courses in AM principles and technologies

There are five major characteristics of the courses in AM technologies at Tsinghua and at a number of other universities:

1. The most frequently used methods of teaching AM technologies do not lead to certain desirable outcomes. Because of the different definitions used for AM (RPM or SFF) and the possible different expectations that are produced, it becomes difficult to clearly explain the difference between AM technologies and some other new advanced manufacturing technologies.

2. Although the excellence of digital manufacturing is quite significant for AM technologies, experts world-wide hold differing opinions as to what constitutes successful achievement with regard to the entire manufacturing industry.

3. There are many decomposition and assembly technologies in the field of AM that deal with different fields of science and engineering such as physics, chemistry, and biology. It becomes difficult to discuss these in a comprehensive manner with any clarity.

4. Different professors and lecturers have different teaching styles. Which of these favor innovation more than others? There is no uniform opinion in this matter, which indicates that the most important factor is practical experience. Students need to perform experiments by themselves, as it is from these that they will derive the greatest profit.

5. What is the appropriate depth of education for the course, and for which students? What elements of each course should be combined with the contents of other courses? How do we know when innovation in education has been successful? We need to know the answers to such questions at the beginning of a course.

2.3 Combining AM with materials and their processing engineering

Current applications of AM technologies require the availability of materials for their processing engineering. The mechanical properties of many types of materials at different temperatures are approaching their end-use in AM technologies. There is a core course in the Department of Mechanical Engineering called Engineering Materials. In addition, there is another important practical course for materials processing, which is called Experiments in Materials Processing. Knowledge of AM technologies was introduced into these two courses at Tsinghua as well as at other universities[10-11].

1. Material applications in AM technologies have progressed rapidly since commercial

technology was introduced in China in 1992. The materials that are available present the most serious restriction, as their properties are still quite limited. We give many examples of material applications in AM technologies in lectures, and students have shown intense interest in this living knowledge.

2. Most AM systems are based on a paradigm of layering, in which physical parts are built up in custom fabrication machines layer by layer, using additive processes with materials. Students have some elementary knowledge in this area and would like to know how to apply this knowledge. This interest that they express could be satisfied by discussion in the classroom.

3. There is another course called Experiments in Materials Processing in the Department of Mechanical Engineering at Tsinghua. This course is a greatly restructured version of an undergraduate engineering education program. The course involves the vertical integration of casting, forging, welding, heat processing, etc. Two experiments in AM are performed in the course. One involves melted extrusion manufacturing technology, using equipment from China, and the other involves plasma spray forming technology on steel substrates, using equipment from Germany. The experiments deal with physical sciences and material science as two interwoven sets of knowledge, which are used together with engineering as the intellectual centerpiece. Students learn the foundations of science in an engineering context, where the focus is on experiential learning and engineering design, with a goal of increased use of technologies.

2.4 Integration of AM with information/computer science and engineering

AM technology is a part of modern manufacturing, which is strongly related to information science and computer engineering. Many universities worldwide have initiated strong efforts to redesign the learning processes in their teaching. We consider that three characteristics characterize innovative education with regard to AM technologies.

1. The work presented at Tsinghua shows the efforts that have been made to implement the method, and provides information on the impact of this innovation on the student profiles. This mission is the result of a consultation process that includes all the teachers at Tsinghua, along with the staff and members of other academic associations and companies in China, and Beijing in particular.

2. Most AM systems are driven by a built-in CAD system. The CAD system usually reads in the part data and determines related processing information depending on the technology. Most CAM support for existing AM systems is proprietary, which is why our laboratory is the one of the divisions of the National Engineering Center of CIMS. The advantages accruing from the CAD/CAM system include processing efficiency, compact data storage, an increased number of control parameters, and most importantly, improved manufacturing time and accuracy.

3. At the present time, there is no tool available for evaluating the impact of the new courses on the students' final profiles. There is, however, a similar course for training in professional education. A number of tools and strategies are currently being developed, and in the meantime, older academic evaluation tools are used for professional education. A national manufacturing game on AM technologies has been staged for professional education in China. Students display many parts and prototypes they have made that represent their creativity and ability to create innovations.

2.5 Courses in bio-manufacturing based on AM technology

There is an urgent need to improve the treatment of articulate cartilage defects. Current treatments for articulate defects have had limited success, in that they are deficient in providing long-term repair, limited in supply, or have unacceptable side effects. Tissue engineering based on AM technology has the potential to develop appropriate replacement tissue endowed with the features necessary for the successful repair of cartilage. We offer two courses related to this field. One, which is for undergraduates, involves the study of bio-materials and the parts of an apparatus. The other, which is for post-graduates, studies the principles and methods of bio-manufacturing (BM). There are also the core courses for students at the Institute of Bio-manufacturing Engineering in Tsinghua, China. The aim of BM, which is an interdisciplinary field of AM and tissue engineering, is to manufacture viable alternatives for defective human tissues or organs. The flexible use of AM is feasible for the manufacture of accurate artificial non-living alternatives, such as prototypes of needed tissues and organs. Moreover, if AM can directly manipulate the cells and extracellular matrix materials (ECMs) as certain forming materials, living replications that actually perform physiological functions could be produced. The courses in BM technologies have four principal characteristics:

1. A rapid ice prototyping (RIP) process was proposed by our lab. This type of prototype was built up using a nozzle at a low temperature in a multifunctional AM system between 1999 and 2001. We have also introduced a finite element model used for simulation of the forming process and distribution of the temperature field. This new technology then migrated to the field of BM. It was proposed that the fabrication technology of multi-nozzle deposition manufacturing take place at a low temperature to fabricate porous tissue engineering scaffolds. The forming room was within our BM system, though only the nozzles were actually inside of it; the moving system was outside the refrigerator.

2. The design and manufacture of a prosthesis for the organism have almost reached a stage of maturity. Many clinical surgeries have been reported that have used orthopedic prostheses. Based on indirect or direct cell assembly, great progress has been made in the bio-manufacture of structural tissues such as skin, bone, cartilage, large vessels, and muscle tendons. Cells seem to be a special bio-material in BM, which makes use of the AM mode of forming. The technology to construct internal organs based on direct cell assembly has become a very hot topic in recent

years. Fig. 4 shows the process involved in computer-aided tissue engineering[12, 13]. We can also see the possibility of producing more precise and more suitable products with tissue engineering.

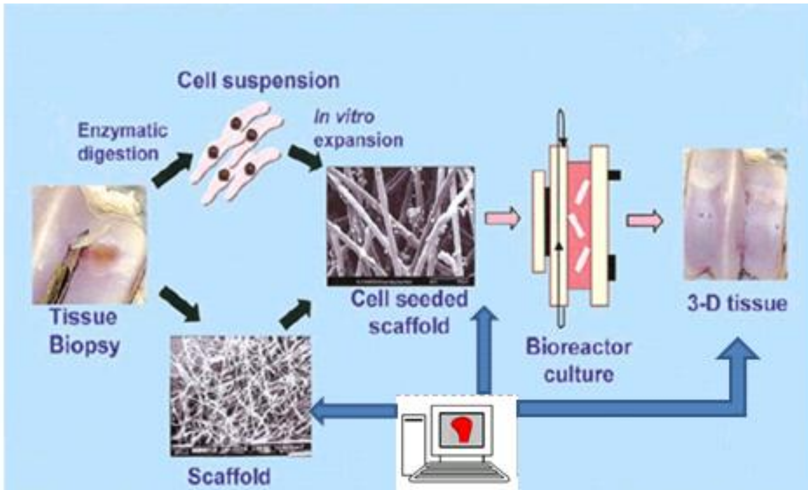


Fig.4 Computer-aided tissue engineering

3. Based on the non-uniform characteristics of bio-materials and cells (including stem cells), we need to develop a new modeling technology for non-uniform materials. To this end, we first established a modeling technology for gradient structures and compositions. We reconstructed the pelvis of a patient from CT scan data to manufacture an AM model that will facilitate the steps of operative planning and prosthesis-making. Such an accurate AM model for a pelvis can help confirm the shape and dimensions of the implant. The BM of the relevant blood vessels requires not only the divergent structure, but also the three-layer structure.

4. We need to pay more attention to the combination of BM with certain conventional conduit fabrication methods such as melt molding, phase separation, immersion precipitation, and solid reaction. It is difficult to precisely control pore sizes and the geometry of scaffolds and their spatial distribution to create scaffolds that have specific and complex 3D anatomical shapes. AM technology has attracted significant interest owing to its potential use in the fabrication of organs.

2.6 Education and training for companies and associations

Associations and mechanical engineering and manufacturing companies have also played an important role in the development of AM in China by interacting with society in the form of seminars and workshops. There are also many companies that offer courses for engineers and technicians in specific fields, which has created a boom in AM in China’s automobile industry. A number of associations and companies have even jointly organized design competitions in vocational schools. By participating in these competitions, students become familiar with the advanced technologies of AM, and gain experience that is is very important for their future work.

AM technology, in particular, is the best combination of hardware and software in the manufacturing field, and 3D AM parts are able to inspire everyone (such as students in professional schools) with great imagination and a high level of creativity. There are a number of national and local contests each year for students in professional schools who produce products using AM technologies?

3. Experimental platform of AM for research and education

Combined with the lectures they offer, all of these universities and colleges are equipped with a laboratory or a setting for experiments. They have also brought in equipment on which students can practice operating software (3D, CAD, etc.) and create prototypes of their own design. Along with the development of AM research in China, the proportion of equipment in Chinese production is increasing as well.

3.1 Multifunctional AM experimental platform

A multifunctional AM experimental platform was established in 1993 in Tsinghua, China. Three types of functions were realized on it: fused deposition modeling (FDM), laminated object manufacturing (LOM), and selective laser sintering (SLS), as shown in Fig. 5a[14-16].

1. The bonding between the material paths in FDM is a key to the strength of the prototypes that are produced. To be able to more easily analyze the relationship between the bonding strength and the forming parameters, the bonding potential, a variable that measures the bonding interface status, was proposed.

2. In research on the process of LOM, the effect of time on the dimensions and weight of LOM prototypes was experimentally studied to identify the stability of the dimensions of the LOM prototypes after the forming process. An increase in dimensions is mainly caused by elastic recovery and moisture absorption.

3. To enhance the scanning accuracy and improve the efficiency of the SLS process, the scanning paths were improved by a number of different methods. The SLS process was performed using wax and powders with a composition of Fe-Ni-Cr.

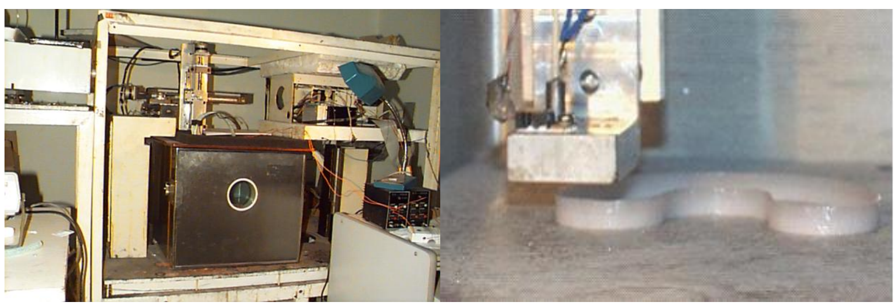
Following the abovementioned research, a new version of the multifunctional AM system was designed and manufactured in our lab, as shown in Fig. 5b. The system has two functions for the multifunctional AM type II device: one is LOM using a laser; the other is FDM using a nozzle, as shown in Fig. 5b.

(a) (b)

Fig. 5 Multifunctional AM experimental platform (a), multifunctional AM machine (b)

3.1.1 The AM experimental platform at low temperatures

In the multifunctional AM system, each functional element is independent. We also introduced a refrigerator into this system, so that RIP prototypes could then be made in it (Fig.



(a) (b)

Fig. 6 AM experimental platform at low temperature

(a) AM system for low temperatures, and (b) nozzle is in the refrigerator

6a)[17, 18]. This system is different from some other systems, such as the one in New Jersey, USA. In that system, the entire moving system was in a large refrigerator, while in our system, only the nozzle is in the refrigerator (Fig. 6b). The software and NC Control, however, are similar to the systems for the other AM processes' systems in the entire system. That said, there are also a number of differences in the hardware to meet the unique demands of this new process. First, the XY scanning device and the Z-axis elevator are all located completely outside the forming room. In this way, there is no need to install a workbench in the refrigerator in which it is impossible to drill or weld. In addition, there is no need to bother considering how to lubricate the three- axis's' motion devices when they are running at a low temperature. Second, since water has a high fluidity and low viscosity, the functional elements related to water supply should ensure that there is a steady water pressure to which fine adjustments can be made. To improve the quality of ice forming, the nozzle extrudes water based upon a drop-on-demand method under the control of a pulse signal. The nozzle is different from the nozzle used in FDM and 3DP.

3.2 The SLA system

The first SLA (stereolithography apparatus) system, which was made by the 3D System Co., USA, was established in 1992 in Tsinghua, China. A number of experiments regarding the properties of epoxy resin and urethane acrylate resin were performed on this equipment; these included investigation of the properties of solidification (curing) and shrinkage, as well as mechanical properties (liquid state and solid prototypes) in the AM process. A number of research efforts for software were also performed on it. Two types of methods for testing the curable properties of photoresins (the stepping-scanning test and window-pane test) were adopted. The forming precision of different photoresins has been investigated using CDT and UPST methods[19].

3.3 Micro-droplet jetting system based on piezoceramic nozzle

One of the main directions of AM development is AM technology based on micro-droplet jetting. In this regard, the numerical micro-droplet jetting of materials is the pivotal technology (Fig. 7). The unique feature of this technology makes it possible for the material layout and part building to take place at the same time. It is also predominant owing to the wide range of applicable materials, and its low cost, simple structure, and ease of integration. This technology is not only the ideal choice as a desktop system in a modern office to create a concept prototype, but it also has the unparalleled characteristic of being able to produce function gradual material. It is also promising in the fields of biomedical and microstructure manufacturing[20-22].

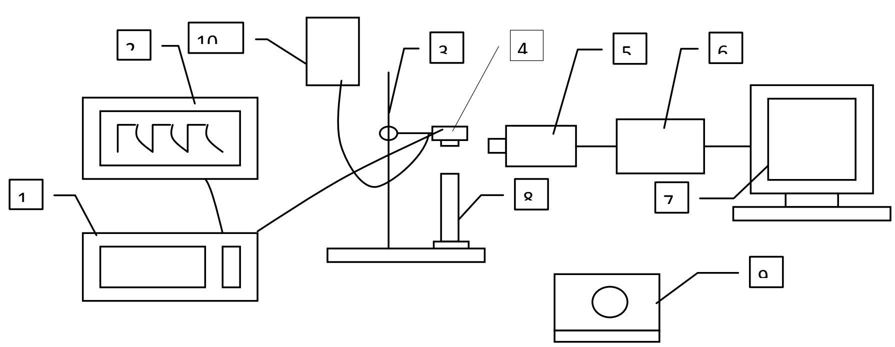


Fig. 7 Schematic of the equipment of micro-droplet jetting

1. Power; 2. Oscillograph; 3. Shelf; 4. Nozzle; 5. CCD camera; 6. Image-grabbing card; 7. Computer; 8. Graduated flask; 9. Electronic balance; 10. Liquid materials container.

A piezoceramic was used as an actuator. The piezoelectric actuator and the structure of the jetting head were designed and the optimized. A special driving supply was designed with high voltage and an adjustable frequency, and it features include simple circuitry, high stability, and low cost. Coupled field analysis and fluid analysis methods in finite element analysis were adopted to analyze the behavior of the piezoelectric actuator and the fluid status during jetting. The vibration characteristics of the actuator, the fluid velocity, and the pressure distribution were studied; as a result, the relationships between the structure parameters and the resonance frequency, the equivalent amplitude, and the fluid state were achieved. Through experiments, theoretical analysis, and numerical simulation, the parameters that affect jetting quality were analyzed, such as the power supply parameters, the structure parameters of the jetting head, and the parameters of the liquid physical property. All these parameters were optimized in the new design to obtain an ideal drop-on-demand jetting status.

3.4 Aerodynamically assisted tip-pen direct writing (TPDW) system

A novel technology called aerodynamically assisted tip-pen direct writing (TPDW) was studied, on the basis of which biomaterials with a wide range of viscosities could be practically manufactured, and a complex 3D architecture could be fabricated. A computer-based digital pressure controller was employed to transport the biopolymer, and to precisely position the microtip. The merits of both features provide a possible method for constructing 3D scaffolds with tissue-scale features (i.e., 10–100 μm) that do not have a deleterious impact on biological activities[23].

The pressure system is based on the utilization of a precision electrical pneumatic proportional valve controlled by a computer (Fig. 8). The optimal structure of the extruder head is obtained by transient thermal analysis using the finite element. Fluid analysis using the finite volume method was adopted to analyze and optimize the fluid status in the nozzle. The problem of nozzle heat sealing has also been solved. Metals such as tungsten and molybdenum were chosen as the most suitable materials because they have the merits of a large elastic modulus and stable chemical properties.

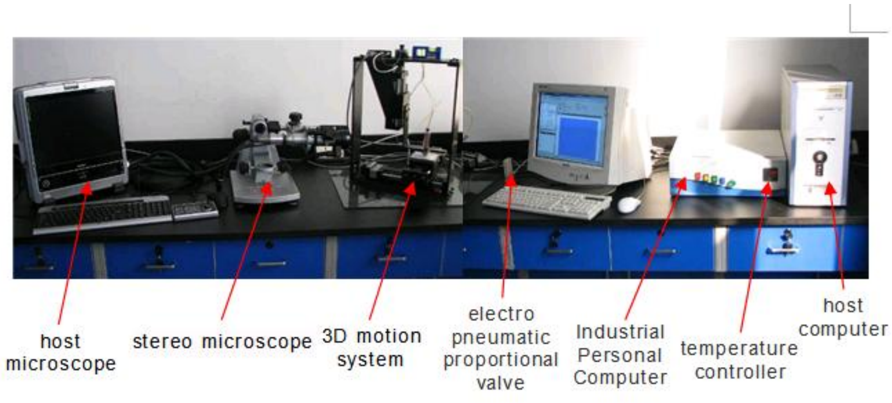


Fig. 8 Tip-pen direct writing (TPDW) system in Tsinghua

The dynamic characteristics of aerodynamically assisted micro-tip direct writing has been researched through transient flow analysis. The dynamical model was established with the application of a transfer function and was simulated using the simulink toolbox of Matlab. Theoretical analysis and experimental research indicated that TPDW has a faster response speed. Using the "Element Birth and Death" technique, the heat effect of a monolayer tube vertical building was simulated. A highly accurate 3D platform controlled by PMAC was set up. Two-dimensional patterning deposition of a number of biomaterial solutions on a variety of substrates was carried out by TPDW. Maltose was selected as the forming material, which was then applied to the fabrication of a series of 3D microstructures. Studies and experiments show that the ratio of the gas pressure to the scanning velocity plays a crucial role in the manufacturing process, and that the diameter of the filament has a negative linear correlation with the diameter of the micro-tip. The experiment's results show that TPDW is able to fabricate complex 3D scaffolds with a feature size of ~50 μm.

3.5 Laser micro cladding deposition manufacturing equipment

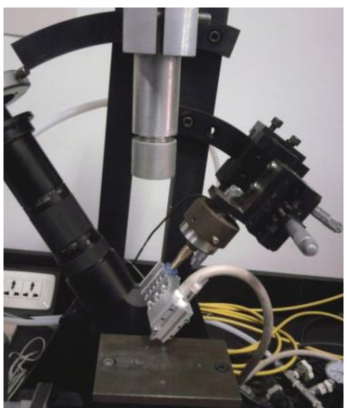


Fig.9 Laser micro cladding deposition manufacturing system

Laser cladding deposition manufacturing is a technology that combines laser cladding technology and AM technology for the building of fully dense parts. Metallurgically sound components are made directly and flexibly in a layer-by-layer fashion from a CAD model without the use of forming dies, tooling, or machining. Experiments were carried out with a laser micro cladding deposition manufacturing system (see Fig. 9), which consists of an ytterbium fiber laser with a 200 W maximum output power with λ = 1070 nm, a precise 3D numerical control working table, a VHX-500K digital microscope, and a powder-conveying apparatus. The powder-feeding nozzle was set at a 50° angle to the substrate surface. The powder-conveying technology employs digitalized micro-fluid technology. The precursor powder is fed depending on the changes in the difference between the inertial force and the friction force. The feeding system includes a powder nozzle made of glass and a piezoelectric actuator, which were developed at the Nanjing University of Science and Technology.

3.6 Multifunctional laser processing and manufacturing system

An advanced processing and manufacturing system based on high-energy laser beams was set up. The technologies involved include laser welding technology, quality control of special materials (aluminum, titanium, zirconium, superconductors, new generations of iron and steel materials, and cemented carbides) and important structures, laser surface modification, and preparation for advanced functional surfaces, on-line quality detection and automatic control of laser processing, and laser direct manufacturing of metal parts based on precise laser cladding.

Fig. 10 shows the precise and flexible AM of a W/Ni alloy component for a hard X-ray telescope collimator with laser cladding for use in outer space[24]. This work entailed the employment of parts with the characteristics of overlap multipass laser cladding of tungsten or tungsten/nickel alloys, followed by analyses of the microstructure and composition of the parts. The laser AM system is composed of a 3 kW fast axial flow CO_2 laser, a CNC-controlled working table, a newly developed computer-controlled powder feeder, and a patent coaxial nozzle. An infrared double wavelength thermometer was used to detect the temperature of the melt pool during the process.

Fig. 10 AM process based on high-energy laser beams

3.7 Electron Beam Selective Melting (EBSM) system

The electron beam selective melting (EBSM) system deals with the direct manufacturing of

Fig. 11 The EBSM 250 in Tsinghua.

metallic parts. Parts manufactured by EBSM have been applied in the fields of medicine, defense, and aeronautics, etc. The EBSM system was established in 2004 in Tsinghua (Fig. 11). Because the electron beam had a relatively large deflection error and the manufacturing precision was lower, a digitized control system was developed[25].

A four-channel, high-speed arbitrary waveform generator was developed, as well as digitized automatic moving software for deflection error correction and dynamic focus control. To improve the deflection accuracy, the non-linear magnetic deflection was analyzed. Experiments proved that such a digitized error correction method could greatly improve the precision of deflection precision and reduce the degree of pincushion distortion.

3.8 Laser-guided direct transportation equipment

Laser-guided direct transportation (LGDT) technology applies optical forces to capture, transport, and deposit single-material particles for the fabrication of structures. Taking various types of particles, including living cells, as manipulable engineered materials, it can act as a new enabling technology for use in rapid prototyping manufacturing systems. Applications can be seen in the fields of microfabrication and tissue engineering. LGDT equipment was installed in our lab and applications for AM were created. Considering the relevant practical influences, experiments and numerical simulations were conducted to investigate the conditions and the rules governing the motions of suspended particles during their transportation. The effects and the mechanisms of those influences were also examined. The guidance and deposition of several types of micron-sized particles, such as polystyrenes, were carried out to learn basic operational and measurement skills, as well as to obtain the essential process parameters (Fig. 12)[26].

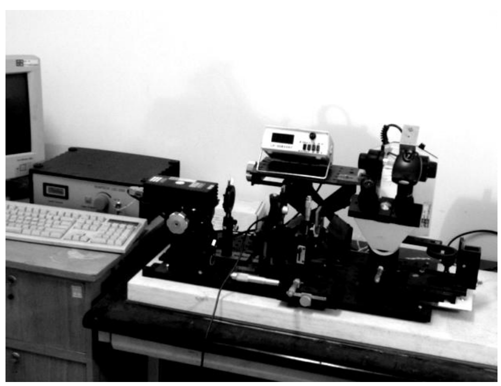


Fig.12 Laser-guided direct transportation system

The driving forces and influences during transportation were discussed next. Based on scattering theory, a computing program was designed that could calculate optical forces precisely. As a result, the distribution of optical forces could be described, giving rise to the conclusion that it is mainly influenced by the optical intensity. The most influential factor during the transportation process is the convection of the suspending medium caused by light absorption. The velocity of the convection can be estimated by a natural convection FEM in an enclosed chamber with an internal heat source. The relevant influential factors were also discussed.

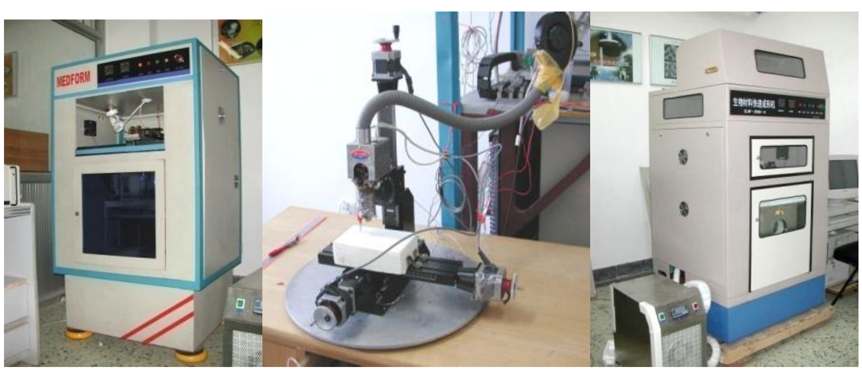
The transportation parameters were discussed in terms of the experimental results and motion simulations. The offset between the particle stream and the optical axis is determined by the change in the equilibrium position of the optical gradient forces, which is itself caused by transverse influences. In addition, the transport velocity of the particles is determined by optical pressures. Both are affected by optical parameters and also by convectional influence, which is similar to optical forces. The conclusions of this paper can be used as references for the design of laser-guided direct writing systems and for their application to rapid forming processes.

4. AM systems for BM

The goal of BM, which is an interdisciplinary field of AM and tissue engineering, is to manufacture alternative defective human tissues and/or organs. Flexible AM technology is feasible for the manufacture of accurate artificial non-living alternatives, such as prototypes of needed tissues and organs. Moreover, natural organs are composed of different types of cells (including stem cells) and ECMs, and these cells are present in the space of ECMs with a specific distribution and orientation. Therefore, if AM can directly manipulate the cells and ECMs as forming materials, living alternatives with physiological functions could be created.

4.1 Four types of BM systems

Four types of BM systems have been constructed at the Institute of Bio-manufacturing Engineering, Tsinghua, China (Fig. 13)[27-30]. The fabrication methods for these four systems are based on an AM technology of adopted droplet assembly. The first system is a BM platform similar to the AM experimental platform at low temperatures, and is shown in Fig. 6. Particles of bio-materials and/or cells are deposited as their droplets are transformed from a solid state to a

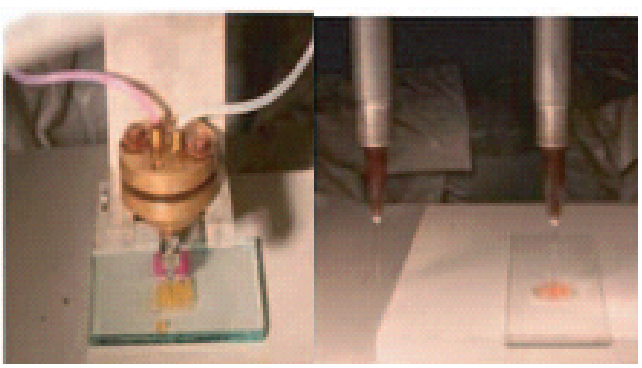


(a) (b) (c)

Fig. 13 Three types of bio-manufacturing systems in Tsinghua
(a) MedForm system for biocompatible materials,
(b) opening bio-manufacturing system, and (c) TissForm system for tissue engineering materials

liquid state. There are many different bio-materials for each of these BM technologies. The MedForm system for biocompatible materials is shown in Fig. 13a. The so-called opening BM system is shown in Fig. 13b. The TissForm system, which has four nozzles, is shown in Fig. 13c. These types of droplets then solidify and assemble at room temperature or at a low temperature, one by one. Three types of materials for bone tissue engineering scaffolds are provided, and they emerge from three nozzles.

The material slurry is formed into frozen scaffolds in a low-temperature deposition manufacturing (LDM) system, such as the MedForm system, for example. First, the material slurry is fed into the material supply, whose bottom is equipped with a soft pipe connected to a screw pump nozzle. The diameter of the outlet of the nozzle is 0.3 mm. The LDM system builds scaffolds layer by layer and is directly computer-driven by 3D digital models. This is accomplished in a low temperature environment of less than 0 ℃ in the refrigerator. The computer controls the nozzle to move in the X-Y plane, extrude the material slurry, and deposit it onto the platform in the area defined by the digital models. The layer of deposited materials is then frozen on the platform. Also, under the control of the computer, the platform then moves down 0.15 mm in the Z-direction after the forming process of each layer. In this manner, the frozen scaffold is stacked layer by layer.



(a) (b)

Fig. 14 Nozzle system in MedForm equipment
(a) Material-mixing single nozzle, and (b) double-nozzle

To ensure the formation of the pores of the vertical cross section, the extruded material is deposited in a series of parallel lines along the Y-direction from the 1st to the 3rd layer, and parallel to the X-direction from the 4th to 6th layer; the scanning direction of the nozzle alternates every three layers. Fig. 14a and b show photos of the single-nozzle and double-nozzle units of the MedForm equipment. The pore dimensions can be adjusted by changing the layer-number interval of the scanning direction and the distance interval of the parallel lines in a single layer. After the forming process, the frozen scaffolds formed by the LDM system are freeze-dried in an ALPHA1-2 Freeze dryer for 38 h to remove the solvent. Following this treatment by freeze drying, the scaffolds remain in the solid state at normal atmospheric temperatures. A quality bio-material system is used in this forming process for bone tissue scaffolds.

4.2 The 3D cell assembler I

Our research group integrated AM technology with a hydrogel solidification process to develop a direct cell-matrix assembly (DCMA) technology[31, 32]. A mixture of high density cells and biocompatible hydrogel materials were chosen as the primary materials, which can be built layer by layer using a controlled sol-gel phase transition between 0 ℃ and 37 ℃ into a 3D cell-containing structure. DCMA technology can be applied to complex problems that require the arrangement of numerous cell types in the proper 3D structure that can then be induced to generate specific biological functions. One newly developed piece of equipment is the 3D cell assembler I (Fig. 15), with which infant rat cardiac myocytes were used to determine the effectiveness of DCMA.

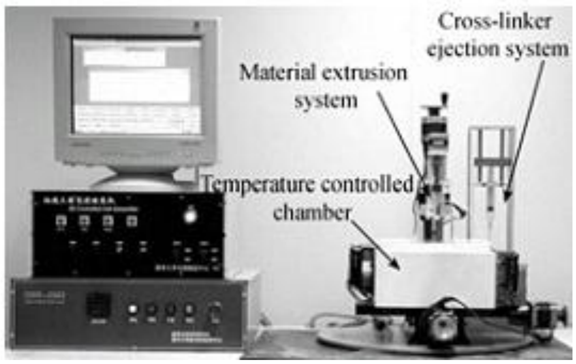


Fig. 15 3D cell assembler I.

Gelatin was dissolved in a hot NaCl (0.15 mol/L, 70 ℃) and Tris-HCl (0.02 mol/L, pH = 7.4) solution to form a 10% (*w/v*) solution that was then filter-sterilized. Sodium alginate was dissolved in a hot NaCl (0.15 mol/L, 70 ℃) and Tris-HCl (0.02 mol/L, pH = 7.4) solution and sterilized twice for 30 min (70 ℃). The solutions were then combined at a 1:1 ratio and mixed thoroughly in a bioclean environment. The isolated cardiac myocytes were mixed into the blended gel at a density of 2×10^8 cells/mL. After thorough mixing, 0.5 mL of the mixture was loaded into a sterilized syringe (1 mL, 0.45 × 16 RW LB). The forming process was carried out following the design structure and programming path at an ambient temperature of less than 10 ℃, using the 3D cell assembler I. The results show that DCMA technology is a promising technology that is currently available to realize the manufacture of complex organs.

4.3 Mechanical stimulation device for AM-BM technologies

The characteristics of the matrix (composition, structure, mechanical properties) and external culture environment (pulsatile perfusion, physical stimulation) of the heart are important characteristics in the engineering of functional myocardial tissue. This study reports on the development of chitosan-collagen scaffolds with micropores and an array of parallel channels (~200 mm in diameter) that were specially designed for cardiac tissue engineering, using a mechanical stimulation device (Fig. 16)[33]. The scaffolds were designed so they would have structural and mechanical properties similar to those of the native heart matrix. Scaffolds were seeded with neonatal rat heart cells and subjected to dynamic tensile stretching using a custom-designed bioreactor. The channels enhanced oxygen transport and facilitated the establishment of cell connections within the construct. The myocardial patches (14 mm in diameter, 1–2 mm thick) consisted of metabolically active cells that began to contract synchronously after 3 days of culturing. Mechanical stimulation by means of high tensile stress promoted cell alignment, elongation, and the expression of connexin-43(Cx-43). This study confirms the importance of scaffold design and mechanical stimulation in the formation of contractile cardiac constructs.

Fig. 16 shows the scaffold and bioreactor design of myocardium cell assembly. Fig. 16A schematically shows the production of a chitosan-collagen channeled scaffold. Polydimethylsiloxane (PDMS) solution was poured onto a laser-cut acrylite disk with vertical channels. After curing at 60 ℃ for 4 h, the PDMS molds were peeled off the acrylite surface and

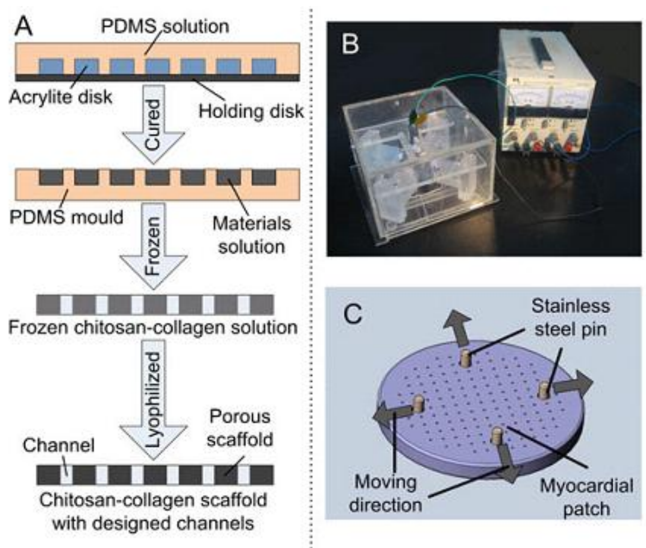


Fig.16 Scaffold and bioreactor design for myocardium cell assembly.

achitosan-collagen solution was poured into the mold. After slow freezing from 4 ℃ to -20 ℃, the sample was removed from the mold and lyophilized to form a porous chitosan-collagen scaffold with an array of channels. A photograph of the mechanical stimulation device, which consists of an adjustable electric source and a chamber, is shown in Fig. 16B. Four sliding blocks are positioned symmetrically inside the chamber to perform back-and-forth movement that is actuated by a motor-controlled cam. Fig. 16C schematically shows the myocardial patches that were installed in the device using four stainless steel pins that were set into four large holes and fixed to each sliding block. The displacement frequency was regulated by the cam geometry and the rotation speed of the motor. The arrows in the figure indicate the directions of the movement of each stainless steel pin.

4.4 New oxidation equipment for the preparation of additive porous anatase titania film

New oxidation equipment, which is presented in a schematic in Fig. 17, is made up of a high-voltage power supply, a stainless steel electro-bath, a blender, and a cooling system. The stainless electro-bath is used as a cathode at the same time. The cooling system is used to ensure that the temperature of the electrolyte remains constant on the whole. The blender is used to improve the uniformity of the electrolyte[34-36].

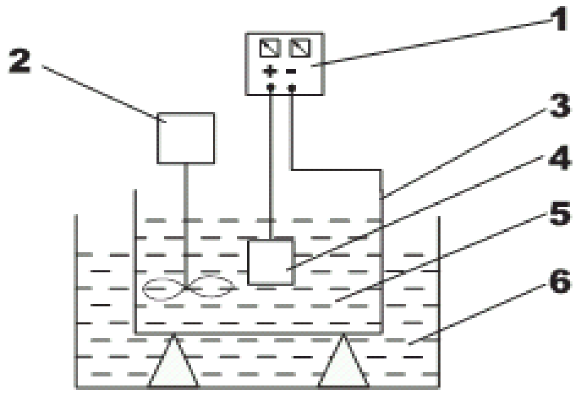


Fig. 17 Sketch of the new oxidation equipment
(1) Power supply, (2) blender, (3) electro-bath-cathode,
(4) titanium plate-anode, (5) electrolyte, (6) cooling water

Porous anatase titanium dioxide with hydroxyapatite coating formed by microarc oxidation (MAO) was made using this equipment. A rectangular Ti grate 1 sample (10 × 10 × 0.4 mm) was used as a substrate. The surfaces of the samples were ground to 1200 grit using silicon carbide sandpaper. This was followed by cleaning with distilled water, acetone, and pickling using a mixture of aqueous HF and HNO_3 acids (with a volume ratio of HF/HNO_3 of 1:3) to remove the native oxide. The samples were then rinsed with distilled water and air-dried prior to pre-anodic oxidation and micro-arc oxidation treatment.

For the pre-anodic oxidation treatment, the pure titanium plate was put into the electrolyte, which was proportioned with 0.05 M oxalic acid and 1000 ml de-ionized water. The titanium plate was the anode and the stainless steel electro-bath was the cathode. The parameters in the pre-oxidation treatment were as follows: the applied voltage was 200 V; the current density was 40 mA/cm^2; the duration was 2 min; a DC power supply was employed in the entire procedure.

Following pre-anodic oxidation treatment, the sample was quickly immersed in the micro-arc oxidation electrolyte, which was composed of 0.02 mol β-glycerophosphate di-sodium penta-hydrate (β-GP), 0.2 mol calcium acetate (CA) and 1000 ml de-ionized water. In the micro-arc anode oxidation treatment, an alternative power supply was used. In the positive section, the processing parameters were: 250 V and a current density of 30 mA/cm^2. In the negative section, the parameters were: 10 V and a current density of 50 mA/cm^2. The processing time for the entire anode oxidation treatment was 10 min, with alternation of the positive and negative electrode at one-minute intervals.

4.5 Microbead generating device for BM

To engineer tissues with clinically relevant dimensions, one must meet the challenge of rapidly creating functional blood vessels to supply cells with oxygen and nutrients and remove waste products. The physiological diffusion of nutrients within tissue is limited to a distance of approximately 100–200 μm from an adjacent capillary. Distances greater than this result in insufficient oxygen to maintain metabolic functioning. As a result, vascular support of the construct is likely to be one of the most critical factors, if not *the* most critical factor limiting the size, maintenance, and quality of an engineered construct. In addition, adipose tissue is a highly vascular tissue that has a capillary filtration coefficient two to three times higher than that in skeletal muscle. These facts suggest that a rich vascular network is crucial to support the demands of an adipose construct[37, 38].

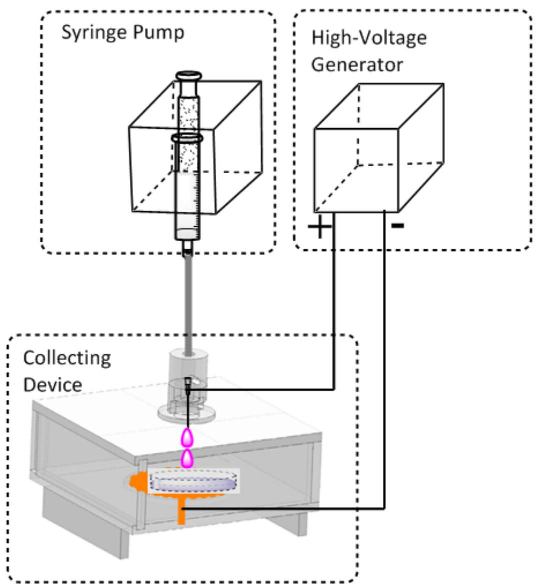


Fig. 18 Schematic of microbead generating device

In brief, the microbead generator is mainly composed of three parts: a syringe pump, a high-voltage power supply, and a collection device, as shown in Fig. 18. The high-voltage field generator (SA167-Y, Tianjin, China) has an AC/DC output voltage ranging from 0 to 40 kV, and the injection pump (TS2-60, Longer Pump Ltd., China) has a promoting speed ranging from 0 to 90 mL/min. The main part of the collection device is a plexiglass box with a pane of sliding glass in the front. A sleeve was set in the center of the upper board, through which a syringe needle and canal were connected to the syringe pump. The sleeve guaranteed perpendicularity, and also facilitated the adjustment of the distance between the needle and the surface of the solidifying solution. A gap was opened in the bottom of the sleeve to facilitate the joining of the positive pole. A copper sheet was inlaid in the center of the bottom board and connected with the negative electrode from the electrical source. 55 mM calcium chloride ($CaCl_2$) solution was used as a solidifying solution and was placed in a 6 cm^2 glass culture dish above the copper sheet. The alginate/collagen hydrogel solution was extruded through the injection pump at a specific speed. When the electrostatic force and the gravity of the solution became stronger than the surface tension, the solution was dragged such that it formed microdrops that fell into the solidifying solution, where they were converted into insoluble microbeads.

One of the fundamental principles of tissue engineering is sufficient vascularization to supply the growth of newly formed tissue. A pilot study was launched whose aim was to induce adipose formation *in vivo* that had mature vasculature, via the subcutaneous injection of co-culture cell microbeads. The microbeads were composed of alginate and collagen, with differentiated human adipose-derived stem cell (hADSC) distributed evenly inside, and human umbilical vein endothelial cells (HUVEC) attached to the surface on the outside. The channels formed by the gaps among the microbeads provided the space for *in vitro* prevascularization and *in vivo* blood vessel development. The endothelial cell layer outside the microbeads was the starting point of vascular ingrowth. Adipose tissue formation and angiogenesis were assessed for 12 weeks at 4-week intervals. The regenerated vasculature within the transplantation showed functional anastomosis with the host vasculature. A relatively persistent volume and weight of the transplants over time was observed, which indicate that the vasculature formed within the constructs benefited from the formation, maturity, and maintenance of adipose tissue. This method has the potential to provide a microsurgical treatment for adipose regeneration.

5. Software and calculation technology in AM

In modern manufacturing technologies, the manufacturing process is usually composed of an information process and a physical process. The application of computer technology in the manufacturing industry has already help realized a digital description of the information process and has strengthened the coordination between the information process and the physical process. This development has resulted in numerical controlled (NC) design and manufacturing, such as computer numerical control processing technology, flexible manufacturing systems, and computer-integrated manufacturing systems (CIMS). Our lab is one division of the national engineering research center of CIMS. This means that study, education, and research in the fields of software and calculation technology are very important to us.

NC design and manufacturing has only achieved a digital information process and the numerical controlling of tools in the forming process. The transfer of forming materials in a physical process is still completely passive, and is not numerically controlled. Unlike NC technology, however, AM technology has realized not only a digital information process, but a digital physical process as well. In AM and BM, the material-transfer process is based on the piling ability of materials. Controlled by digital information, forming materials are added on-demand and are gradually accumulated in the forming area, step by step, to give shape to the final parts, which further enhances the flexibility of the formation process[39-41].

For BM technology in particular, the forming materials include biodegradable materials and even cells, as living materials. The physical forming process still remains a process of materials undergoing change. The usual modeling methods need to be alternated. According to the levels of application of AM, there are three stages of BM. The first stage is organ prosthesis manufacturing, which can be divided into two classes, according to whether or not the prosthesis will be implanted. The second stage is indirect cell assembly, which refers to a two-step method of fabricating tissue or organs. The third stage is direct cell assembly, which refers to the direct manipulation of cells, biomaterials, and growth factors, and their deposition at a specific spatial site according to a digital model, whose design is based on an anatomical model of an organ or tissue. In all 3D cell assembly technologies such as cell printing (organ printing and bioprinting), 3D photopatterning, laser-guided direct writing, 3D assembly, and 3D direct controlled cell assembly, certain types of thermo-reversible biomaterials such as gelatin, alginate, chitosan, and fibrin can be mixed with cells and can then be extruded into a low-temperature forming chamber to fabricate a living construct.

5.1 Digital models of a hybrid construct for BM

Here, we discuss an example of digital models of a hybrid construct for BM. The liver is a huge chemical plant that plays an important role in metabolic processes. It is composed of two branched vascular networks and numerous hepatic lobules. The blood supply system is quite extensive and important for the liver's functions. Nutrients, including O_2, are transported through dendri-form vascular networks into every part of the liver, whereas wastes, including CO_2, are simultaneously carried out[42, 43]. Fabricated liver analogs must therefore mimic these special characteristics. Figure 19 shows a branched vascular model that was designed in our laboratory. The red tube-like part was predefined as the branched walls of the vascular system, the yellow part was designed to serve as hepatic tissues (Fig. 19d), and the cyan part was used as a covering

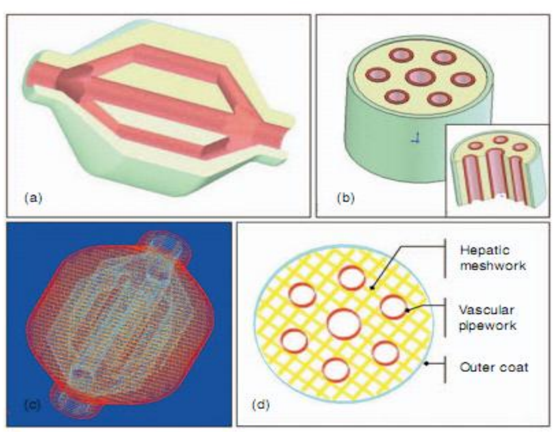


Fig.19 Illustrations of digital models of a hybrid construct for the liver (the red tube lines denote the vascular network; the yellow part is expected to form hepatic tissues)
(a) Cutaway view of the full model with branched network, and one-way inlet and outlet for dynamic perfusion culture; (b) cross-sections of the middle part of (a); (c) a CLI result of (a); and (d) a single CLI layer of (b).

for the entire structure (Fig. 19a, b, and d). The one-way inlet and outlet structure was designed to be connected with a bioreactor to provide for *in vitro* dynamic perfusion culture. Using the preprocessing software Aurora (Yinhua, China), the digital model was transferred to a common layer interface (CLI) file for digital-controlled fabrication at a later time. Fig. 19c shows a CLI derived from Fig. 19a and 19d, which are two of the CLI layers derived from Fig. 19b. Except for the round tubes, the yellow part was woven with crossing threads, thereby providing a secondary meshwork or interconnected macro channels for the exchange of nutrients and waste.

5.2 Model of design and control of macro-cellular morphology

Scaffolds are temporary *in vivo*, and they gradually degrade, in a process that is accompanied by bone regeneration. For this reason, complicated bony structures can be simplified for the convenience of the macrocellular morphology, although several basic requirements must still be satisfied. Scaffolds fabricated in our MedForm equipment are all composed of a series of crossing parallel lines (Fig. 20a)[44]. The extruded slurry was deposited along the Y direction from the 1^{st} to 3^{rd} layers, then along the X direction from the 4^{th} to 6^{th} layers. The scanning directions were alternated every three layers, and highly interconnected and crossed macropores were then formed by the intervals among the lines (Fig. 20b), through which cells could enter all over the scaffold. The line width w could be calculated approximately by the nozzle diameter d_N, the layer height Δh, and the slurry's flow-ability.

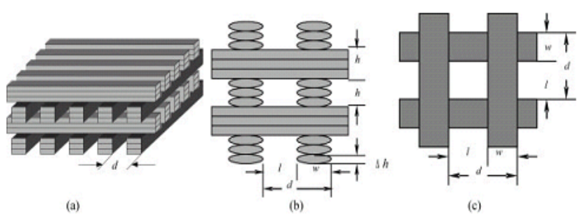


Fig. 20 Megascopic macrocellular morphology designed for LDM

5.3 Bone scaffold hierarchical algorithm based on STL data model

On the basis of data models, including stereolithography (STL) and contour layer interface (CLI), a hierarchical algorithm of a bone scaffold was obtained in the fields of AM and BM, and the data structure and class diagram of an extended model from the angle of a prototyping software system could be generated. An STL file integrates many triangular patches and is expressed by three climax coordinates, and four data items of its outward normal vector were introduced. Because an STL data model describes the structure of a single entity and the data information of CLI models of a single entity patch is obtained following the dispersion, it does not include changes in gradient structure and gradient material[45, 46].

We adopted the operating system of Windows XP, and used the development environment of Visual C++ and a 3D graphic software library (Open Graphics Library), independent of the operating system, window system and hardware environment, and developed a data processing software system. The BM device was used to drive the shaped hardware unit in the prototyping test. Fig. 21 shows the functions of the software structure that were used for fabrication of the bone scaffold. The interface module was used to realize the data input and output, and the user demands could be executed to browse files in different formats. The display module was used to show graphic pictures of opened files and the matrix transformation of models by OpenGL. The support module was used to provide stable prototyping of the supporting frame and reduce the warping of the auxiliary configuration in terms of material properties, strata configurations, quantity scale, and scan ruling. The filling module was used in the process of filling the composite material unit and the construction material unit between the inner and outer contours of the material structure domain. The layering module was used to realize the special information of the supporting frame modeling, and to design and complete the entitative internal structure information, except for simple geometrical coordinate data. The control module was used in the initialization of the numerical control system, and the setting of layering information, path scanning, and processing prototyping.

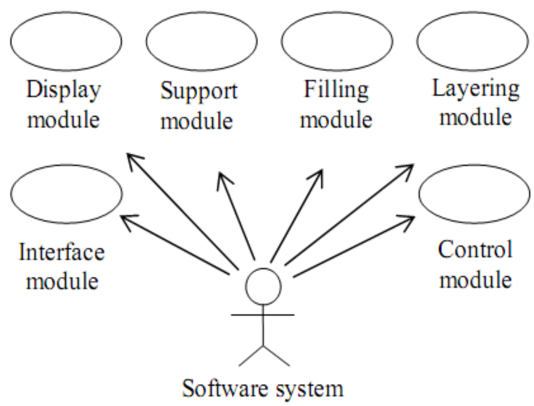
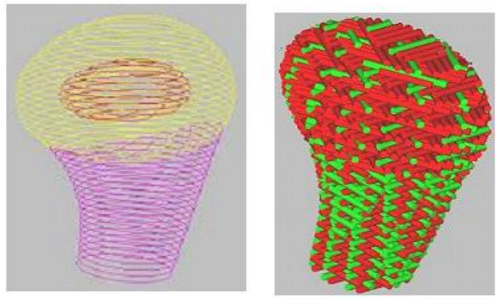


Fig. 21 Functions of the software structure for fabrication of a bone scaffold

Fig. 22 shows the test results. Fig. 22a shows the result for the stratified interface functions of the bone scaffold model; Fig. 22b shows the filling material for the structural fill model. We can ascertain from Fig. 22 that the bone scaffold hierarchical algorithm contains plural property information for bone scaffold materials, multiattribute characteristics of structural changes, and pore structure information of the bone scaffold for tissue engineering, particularly gradient information of composite materials and structures.



(a) (b)

Fig. 22 The output of structural drawing of bone scaffold model
(a) and illustration of the filling material for structural fill model

In the future, more attention needs to be paid to the integration of data resources, as this will provide us with the essential parameters of AM technologies so that valid data resources, including materials, structures, regions, sprayer, path and filling scan can be established. This could also provide us with the data support that is indispensable for in-depth research in hierarchical algorithms.

6. Conclusions

In conclusion, we would highlight the following points regarding the science and engineering of the AM technologies:

1. Innovative education plays an important role at a high level. Its success depends not only on coursework, but also on experimentation and training opportunities. The four-year undergraduate engineering education should be designed so as to provide students with the knowledge base and intellectual capability to both continue their study and directly engage in practical work. The focus of an undergraduate engineering education should be the development of students as emerging professionals, rather than as fully trained engineers.

2. Because the AM technology has emerging and developing characteristics, it can be readily combined with the study of mathematics, physics, and chemistry, and particularly owing to its relationship with computer engineering, it could be used as a powerful tool for innovative education.

3. More attention must be paid to the construction of the AM and BM laboratory. Though our department has more complete and advanced equipment and devices than it did previously, this significant step forward still constitutes just a first step. A very long road of progress still lies before us. The equipment and devices needed for this progress will need to be designed and fabricated by ourselves.

4. Academic communication on an international level is very important. AM systems can quickly produce models and parts from 3D CAD model data. CT and MRI scan data are obtained from other 3D digitizing systems; the BM technologies were indicated from these data. Using an additive approach to building shapes, the AM and BM systems can combine liquids, powders, sheets, or even living cells to form physical objects. Their most prominent characteristic is their ability to produce real parts from a virtual model.

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