Photo-curing 3D printing technique and its challenges

Haoyuan Quan, Ting Zhang, Hang Xu, Shen Luo, Jun Nie, Xiaoqun Zhu*

College of Materials Science and Engineering, Beijing University of Chemical Technology, Beijing, 100029, PR China

ABSTRACT

In recent ten years, 3D printing technology has been developed rapidly. As an advanced technology, 3D printing has been used to fabricate complex and high-precision objects in many fields. 3D printing has several technologies. Among these technologies, photo-curing 3D printing was the earliest and most mature technology. In 1988, the first 3D printing machine which was based on photo-curing and called Stereo lithography Appearance (SLA) technology was produced by 3D system Corp. After 30 years of development, many new technologies based on photocuring mechanism emerged. Based on the different principle of pattern formation and character of printing technology, numerous photocuring 3D printing techniques, such as SLA, DLP, LCD, CLIP, MJP, two-photon 3D printing, holographic 3D printing and so on, have been developed. Photo-curing 3D printing has many advantages, such as high precision, smooth surface of printing objects, rapid printing speed and so on. Here, we would introduce five industrial photocuring 3D printing technologies, which are SLA, DLP, LCD, CLIP and MJP. The characters of the materials and the progress of the application of the technique in the biomedical field is also overviewed. At last, the difficulties and challenges of photo-curing 3D printing are also discussed.

1. Introduction

3D printing, commonly known as additive manufacturing technology, is a practice of making three dimensional objects through layer by layer printing [1]. 3D printing technology is an interdisciplinary technology which includes machinery, computer technique, numerical control, material technology. Usually, the process of 3D printing contains three steps: firstly, the design of the 3D models by computer modeling software; secondly, the 3D model being cut into slices; finally, printing the model layer by layer [2]. Thus, in theory, any complex three-dimensional model could be fabricated by 3D printing technique [3]. The applications of 3D printing have expanded not only covering traditional manufacturing but also electronics, medical and other industries. 3D printer can print almost any item ranging from small thing such as jewelry, toy, gadget, teeth to large one such as engine, car, house and so on [4].

Since the concept of 3D printing technology was proposed in 1980s, 3D printing technique has been developed rapidly and many technologies were appeared [5]. Among these 3D printing techniques, photo-curing 3D printing is the earliest 3D printing technology. It is based on photo-polymerization technique and the photosensitive liquid resin is used as material. The resin could be cured only under light irradiation. Without irradiation, the resin keeps liquid. Thus, after printing, the models could be separated from resin easily and quickly. Due to the high precision and fast polymerization rate of photocuring technique, the models could be rapidly printed.

According to the principle of pattern formation and the control system, photocuring 3D printing had different techniques, such as stereo lithography appearance (SLA), digital light processing (DLP), liquid crystal display (LCD), multi-jet printing (MJP), continuous liquid interface production (CLIP), two-photon 3D printing(TPP), holographic 3D printing technology and other printing technologies [6]. The photocuring 3D printing technique has high printing speed, high precision, and the printing objects have smooth surface. However, due to being limited by the performance of photocured material, which is brittle, easy to deform, bad weather resistance and low biocompatibility, at present, the photocuring 3D printing technique and materials mostly used in the field of temporary replacement material, such as dental restoration, dental orthodontic, dental surgery, model, die and so on.

In this review, we would like to introduce relatively mature and commercialized photocuring 3D printing techniques, mainly including SLA, DLP, LCD, CLIP and MJP techniques. The characters, advantages and disadvantages, applications of each kind of photocuring 3D printing would be introduced. Moreover, the challenges and the
opportunities of the photocuring 3D printing would be discussed in the end.

2. The techniques of photo-curing 3D printing

2.1. SLA 3D printing

2.1.1. Technique overview

As the earliest technique of 3D printing, SLA technique is the most mature 3D printing technique and widely used in the industry. This technique was patented in 1986 by Charles Hull, co-founder of 3D Systems, Inc., a leader in the 3D printing industry. In present, large industrial photocuring 3D printing machine is mainly based on SLA technique.

Commonly, the wavelength of lamp used by SLA machine is 355 nm laser beam, the laser beam is above the resin tank and the exposure direction is from the top, the liquid resin is solidified when scanned by laser beam. A platform is lowered into the resin; thus, the surface of the platform is a layer-thickness below the surface of the resin. The laser beam then traces the boundaries and fills in a two-dimensional cross section of the model, after a layer of resin cured, the platform descends a distance with one layer, solidification is repeated through layer by layer until a solid 3D object is produced [7]. The pattern formation of every layer is controlled by the moving of laser beam. In theory, the laser beam could move over a large space. Therefore, the SLA printing technique could print large size models.

2.1.2. Material overview

The materials used in photocuring 3D printing is photosensitive resin. The photocuring mechanism would be chosen depending on the wavelength of the lamp and printing technology. Generally, the photosensitive resin which used in the SLA technique is based on the mechanism of cationic photopolymerization or hybrid photopolymerization [8]. There are three reasons for choosing such mechanism. Firstly, the wavelength of laser beam of SLA is 355 nm. At this wavelength, both radical and cationic photopolymerization could be proceeded; Secondly, volume shrinkage is the fatal weakness to photopolymerization, it could induce the strong internal stress which caused the deformation of material, eventually, the material would be broken. Otherwise, volume shrinkage results in the decline of the precision of printing model. Thus, volume shrinkage is disadvantage to the photocuring 3D printing and scientists try to overcome it [9]. It is well known that cationic photopolymerization has low or no volume shrinkage [10]. Therefore, if the light source matches with the absorption of cationic photoinitiator, cationic photosensitive resin is good choice to the photocuring 3D printing. Thirdly, the resins for cationic photopolymerization are less and the price of initiator is high, on the other hand, the photopolymerization induction period is long, thus, hybrid photosensitive resins, which means mixture of radical and cationic photosensitive resins, are often adopted. The hybrid resins could adjust the performance, printing rate and price of printing models.

2.1.3. Advantages and disadvantages of SLA technique

SLA is the earliest rapid prototyping technology with high maturity, stable printing process and numerous machine suppliers. Up to now, SLA is the only photocuring 3D printing technique which could print large size models. But SLA has low printing rate due to the curing rate depending on the moving of the laser beam. The larger size of the models, the slower the printing rate. In addition, the resins available for the cationic photopolymerization are limited [11]. The printing resolution depends on the size of laser beam, thus, compared with other photocuring technique, SLA has low resolution [12]. Even so, the precision of SLA technique is good enough to print the objects with complex structure and fine size. Until now, SLA is still an important printing technique and could be used in many fields, such as dental, toys, molds, automotive, aerospace field and so on [13].

2.2. DLP 3D printing

2.2.1. Technique overview

DLP uses a projector, like the one used for office presentations or in-home theaters, to project the image of the cross section of an object into photosensitive liquid resin. The key technology of DLP 3D printing is DLP technology which determines the image formation and printing precision. The emergence of DLP technology has been 20 years. The core part of DLP technology is the optical semiconductor, or digital microwave device or DLP chip, which was invented by Dr. Larry Hornback in 1977 and commercialized by Texas instruments in 1996 [14]. The DLP chip is probably the most advanced optical switching device in the world to date, containing two million regular arrays of tiny microscopes that hinge on each other. Each microscope is about a fifth the size of a human hair. When the DLP chip coordinates with digital video or image signals, light sources, and projection lenses, the microscope can project a full digital image onto a screen or other surface. The advanced electronic devices of DLP and its peripherals are known as Digital Light Procession technology (data optical processing). The microscope switching times of DLP chips can reach thousands of times per second, reflecting the gray shadows of 1024 pixels, converting video or image signals input from DLP chips into rich grayscale images. Therefore, DLP 3D printing has high printing resolution which could print minimum size of 50 µm. Because semiconductor packaging materials do not tolerate UV light, the LED lamp with the wavelength of 405 nm is the light source of DLP 3D printing machine. DLP 3D printing is plane exposure, but the exposure area is limited. At present, the printable size can be 100*60 mm to 190*120 mm. The DLP 3D printing has the advantage to print the objects with small size and high precision [15].

2.2.2. Material overview

Normally, the free radical photosensitive resin is used for DLP 3D printing. The reasons why do not use cationic photopolymerization are: Firstly, cationic photoinitiator could hardly work under 405 nm irradiation, some cationic photoinitiator could work under 405 nm, however, the price is too high to constrain its application. Secondly, the light intensity of DLP 3D printing is not high enough to photolysis the cationic photoinitiators, which can’t induce the photopolymerization [16].

2.2.3. Advantages and disadvantages of DLP technique

The high precision is the greatest advantage of DLP 3D printing [17]. However, to guarantee the high precision, the size of the projection is limited. Therefore, DLP 3D printing only could print small size objects. On the other hand, the DLP technology is dominated by Texas instruments company and the price is high, therefore, the DLP 3D printer is very expensive [18]. Because DLP 3D printing technology has the character of high precision, meanwhile, it could only print the model with small size, thus, it is mainly used in the fields of jewelry casting and dentistry [19].

2.3. LCD technique

2.3.1. Technique overview

Throughout all photocuring 3D printing technologies, from the laser-scanning SLA, to digital projection DLP, to the latest LCD printing technology, the main difference is the light source and imaging system, while, the control and stepping system have little difference. The biggest difference between DLP and LCD 3D printing technology is the imaging system. To LCD 3D printing technique, the liquid crystal display is used as imaging system. When an electric field is applied to a liquid crystal, it will change its molecular arrangement and prevent light from passing through. Thanks to the advanced liquid crystal display technology, the resolution of liquid crystal display is very high. However, during the electric field switches, small number of liquid
crystal molecular cannot rearrange, resulting in weak light leakage. This caused the precision of LCD printing technology is inferior to the DLP [20].

2.3.2. Material overview

In addition to the printing accuracy, the major difference between DLP and LCD 3D printing is the light intensity [21]. It is well known that light intensity is an important factor for photopolymerization which determines the speed of printing and curing degree. Therefore, only if increase the amount of initiator or extend the exposure time, the photosensitive resin for DLP 3D printing could be used in LCD 3D printing.

2.3.3. Advantages and disadvantages of LCD technique

LCD machine is very cheap, and has good resolution. However, the LCD has a short service life and needs to be replaced regularly, the light intensity of LCD 3D printing is very weak, because only 10% of the light could penetrate from the LCD screen and 90% of light is absorbed by the LCD screen. Moreover, as mentioned above, the partial light leakage could result in the transition exposure of photosensitive resin at the LCD screen. Moreover, as mentioned above, the partial light leakage could result in the transition exposure of photosensitive resin at the LCD screen. Therefore, the partial light leakage could result in the transition exposure of photosensitive resin at the bottom, the liquid tank needs to be cleaned regularly. Now the LCD 3D photocuring machine is applied in the fields of dentistry, jewelry, toys and so on.

2.4. CLIP technique

2.4.1. Technique overview

On March 20, 2015, the CLIP technology (Continuous Liquid Interface Production), which was developed by Carbon 3D Corp, was reported on the cover of Science [22]. The key of this technique is the invention of the oxygen permeation membrane which helps the consecutive printing for the oxygen permeation to inhibit the radical polymerization. CLIP technique is an advanced technique of DLP. The basic principle of CLIP technique is not complicated, UV projection at the bottom makes photosensitive resin solidify, while the liquid resin at the bottom of the tank maintains a stable liquid area due to oxygen inhibition, thus ensuring the continuity of curing. Special window at the bottom allows light and oxygen to pass through. The most important advantages of the technology is that it can be used to produce objects in a disruptive way—25 to 100 times faster than DLP 3D printer, and the theoretical potential printing rate could go up to 1000 times of DLP technique and the stratification can be infinitely fine. The present 3D printing requires to cut the 3D model into many layers, similar to the superposition of slides, which results in that the roughness cannot be eliminated. While, the projection of the images of the CLIP technique can be continuous change, which is equivalent to the slide evolving into superposition video. This is a huge improvement over DLP projection technology [23].

2.4.2. Material overview

Technically, CLIP technology is an upgrade of DLP technology, since both the light source and the imaging system are identical. Theoretically, the photosensitive resin used in DLP 3D printing could also be used in CLIP 3D printing. However, CLIP technology has high requirement on the viscosity of materials, especially in the case of rapid printing speed. It is easy to know, the rapid printing requires that liquid photosensitive resin can quickly move to the print area. Obviously, low viscosity resin with good fluidity can flow to the printing area in time, whereas the high viscosity resin has bad fluidity which causes the decline of print speed or the failure of print. Therefore, to the high viscosity resin, the advantages of rapid printing of CLIP technique would be lost.

2.4.3. Advantages and disadvantages of CLIP technique

It can be said that CLIP technology is the real 3D printing. It’s a subversive technology to the present 3D printing technology. Undoubtedly, the greatest advantage of CLIP technique is the rapid printing. Nevertheless, there are still some technique problems to be solved. Up to now, to achieve the rapid printing through CLIP technique, low viscosity resin and hollow model are required. The former ensures the fast complement of resin to the printing area, while the latter reduces the quantity of the resin which is needed every layer. Therefore, to the high viscosity resin and the solid models, the efficiency of CLIP technique is not high. In addition, the oxygen permeation membrane is expensive.

2.5. MJP technique

2.5.1. Technique overview

MJP technique, is also called PolyJet, patented by Objet, an Israeli company in 2000. The MJP 3D printing could print models efficiently, for many arrays of nozzles work together. According to the model slice data, hundreds to thousands of nozzles spray liquid photosensitive resin layer by layer on the platform when working, the printing nozzles move along the XY plane. When the photosensitive resin is sprayed to the working table, the roller will treat the surface of the sprayed resin flat, and the UV lamp will cure the photosensitive resin. After finishing the spray printing and curing of the first layer, the device’s built-in workbench will drop a layer thickness with extreme accuracy, and the nozzles will continue to spray the photosensitive resin for the next layer of printing and curing. Repeatedly, until the entire workpiece is printed. Meanwhile, some other nozzles are responsible for printing fusible or soluble support materials [24].

2.5.2. Material overview

Unlike SLA, DLP, LCD and CLIP 3D printing, the imaging control and lamp source of the MJP 3D printing are independent. In theory, the wavelength of the light source of MJP printing can be unrestricted. Thus, to MJP 3D printing, radical, cationic and hybrid photo-polymerization could be chosen. In addition, the viscosity of the resin is important to the MJP 3D printing for the ink-jet needs low viscosity to ensure the ink injectable. Therefore, the low viscosity or nozzle with heating device is prerequisite.

2.5.3. Advantages and disadvantages of MJP technique

To MJP 3D printing, different materials can be sprayed for there are lots of nozzles. Thus, a variety of materials, multi-color materials could be printed at the same time, which can meet the needs of different materials, different colors, different stiffness and so on. Until now, MJP 3D printing is the only technology which could print multi-color models. MJP 3D printing has very high processing accuracy, which can print layer thickness as low as 16 μm. For the supporting materials are fusible or soluble, the process of removing the supports is damage-free and easily. Therefore, the surface of the printing models is smooth. At last, in theory, the print size is unlimited. However, the MJP printer machine is very expensive. The materials are also expensive and low viscosity is required. MJP technology could be applied in the fields requiring high processing precision. Now it is often used in the jewelry casting, precision medicine and so on.

Table 1 summarized the important characters of different photocuring 3D printing techniques.

3. The progress of photocuring 3D printing technique in biomedical applications

Photocuring 3D printing technique requires the printed materials to have photosensitive property. Commonly, the printed material is composed of photoinitiator, resin and monomer. However, to the biomedical application, the good biocompatibility is the most important property to the materials. However, most of the photosensitive resin materials are cytotoxic, due to the unreacted double bond, residual photoinitiator and so on. Therefore, photocuring 3D printing technique
is not widely adopted in the biomedical applications. Nonetheless, photocuring 3D printing technique still has some applications in the field of biology such as indirect or transient contact with living body. Photocuring 3D printing materials for direct and long-term contacting with living body are still in the academic research.

### 3.1. The progress of application in indirect or transient contact with living body

Until now, the performances of biocompatibility are still the shortages of photocuring 3D printing material. Thus, the photocuring 3D printing material can be applied industrially on a large scale is mainly in the fields that do not require the direct contacting with the living body. Among these, the dental material fabricated by photocuring 3D printing is the largest consumption. 3D printing technique brought great innovation to dental technology. In the dental field, nearly all the gypsum models could be replaced by resin models which are fabricated by photocuring 3D printing. These models involve in orthodontic model, repair model, and so on. Besides, dental surgical guide which is transitory contact with oral mucosa is another dental material printed by photocuring 3D technique. Once the models are fabricated by photocuring 3D printing, the accuracy and efficiency of orthodontic and dental repair technology is improved greatly. Also, the mechanical strength of resin model, especially the abrasion resistance and toughness, is greatly improved. Since the size of these dental models are relatively small, except two-photon printing technology, the other photocurable 3D printing technologies can be used to print dental models. Among all dental models, dental orthodontic models have relatively low requirement of accuracy, and even SLA with relatively poor printing accuracy can meet the requirement. In industry, mass production of dental orthodontic models is printed by SLA technology, because the molding size of SLA technology is the largest, which can print dozens or hundreds of models each time. For small clinics or hospitals, DLP and LCD are used more often, for the quantity of the models is not so much. At present, DLP and LCD are the main technologies to be used to print repairing model and the surgical guide because of the high precision.

Except in the dental field, photocuring 3D printing technique is also used to print the auxiliary medical model. 3D printing medical model can be used for medical teaching, pre-operative simulation and case discussion. Visualization of the model can assist the surgeons to explain the state of an illness to patient and to help the preoperative disease analysis. It is beneficial for surgeons to simulate some complex operations, make the best operation plan, improve the operative successful rate and surgical results. Medical models are currently used for surgical simulation, spinal surgery, plastic surgery, otolaryngology and other surgical procedures.

| Technique | Lamp source | Printing size | Photocuring mechanism | Precision |
|-----------|-------------|---------------|-----------------------|-----------|
| SLA       | 355 nm Laser beam | No limit | Hybrid photocuring | Fair     |
| DLP       | 385–405 nm LED lamp | Limited | Radical photocuring | Very good |
| LCD       | 405 nm LED lamp | Limited | Radical photocuring | Good     |
| MJP       | No limit No limit | Radical, cationic, or hybrid | Outstanding |
| CLIP      | 385–405 nm LED lamp | Limited | Radial photopolymerization and thermal polymerization | Very good |

### 3.2. The progress of application in direct contact with living body

So far, photocurable 3D printing has been difficult to be used in humans directly due to the low biocompatibility of photosensitive resin. Now, materials that can directly contact with human body through photocuring 3D printing are mainly inorganic materials. Bone materials with biological activities, such as hydroxyapatite and biological glass, are not photosensitive materials and need to be mixed with photosensitive resin. Therefore, the biological activity of products will be greatly affected after printing. Generally, after photocuring 3D printing, the material is dealt with sintering to remove the resin, leaving only the inorganic part, which is expected to be used as a substitute material for bones, teeth, etc. However, the volume shrinkage caused by the removal of organic matter needs to be compensated by software compensation technology, while the data calculation of special-shaped materials is very large, this software technical is not mature enough at present. At the same time, due to a large number of inorganic material filling, the resin is like paste and could not flow. Therefore, the photocurable 3D printing equipment for printing inorganic materials is unique. None of the printing devices described above can be implemented. More biomedical photocurable 3D printing materials are still in the academic research stage, involving scaffold printing, hydrogel printing and cell printing. Cui et al. [25] used PEG-DMA/chondrocyte mixture solution as bio-link to print cartilage defect sites under ultraviolet light. The result showed the cell survival rate was relatively high. However, in the process of photocurable printing, several factors, such as the photopolymerization reaction, different wavelength, laser power, exposure time and photoinitiator, affect the cell activity inevitably [26], to some extent, limited the application of this print mode.

Some research groups prepared degradable biomedical support through photocurable 3D printing. It is known that polycaprolactone (PCLS), poly (lactic acid) (PLA), and medical polyurethane (PU), which is synthetic material, has been proved of good biodegradability and biocompatibility, and is widely used in the field of tissue engineering. Petrochenko et al. [27] used the photosensitive resin which was composed of polyurethane diacrylate (UDA) resin (Genomer 4215), two photosensitive diluents, 2-hydroxy-ethyl acrylate and glycol diacrylate to print support by SLA 3D printing technology, the printed sample was washed by 70% ethanol and 30% acetone solution repeatedly to remove the unpolymerized resin and diluent. Thus, the honeycomb scaffold with a porosity of up to 60% was obtained, mesenchymal stem cells (MSCs) were seeded on the surface of this honeycomb scaffold, it was found that the cells could be distributed on the porous scaffold evenly with a high adhesion rate, the pseudopodia of the cells were closely attached to the surface of the scaffold. With the regeneration of tissues or organs, the biodegradable scaffolds begin to degrade gradually, when the new tissue is fully grown, the scaffolds also completely degrade. Danilevicius et al. [28] successfully prepared tissue engineering scaffolds with three-dimensional porosity using PLA materials though SLA printing technology. They investigated the effects of porosity of scaffolds on physiological characteristics such as cell growth, adhesion and reproduction, the results showed that 3D printing technology can control arbitrary voids and porosity during the preparation of PLA tissue engineering scaffold model.

It is certain that photocuring 3D printing technology has many advantages, but its development and popularization in the field of biomedical materials are still limited by many factors. (1) Printing technique limitations: different photocuring printing technique has different lamp wavelength, printing size, the requirement of viscosity of resin, and so on. (2) Material limitations: the biomedical material which could be photo-cured is quite less. While, at present, the technique of photocuring 3D printing requires the resin with low viscosity. Thus, there are fewer options of materials which are suitable for biomedical materials. At the same time, the national standards on 3D printing materials have not yet been established well. (3) The limitations of cost.
price; the price of biomedical materials restricts the photocuring 3D
printing technique in the tissue engineering experiment and clinical
test. In summary, it would be a long way to use the photocuring 3D
printing technique to fabricate the biomedical materials.

In the practical application, most of the photocuring 3D printing
materials do not contact with the human body directly, such as in the
field of dental restoration, dental orthodontic, dental surgery and so on.
While, the application in biomedical field is mainly in the academic
research stage [29,30]. Custom-made capacity and high precision of the
photocuring 3D printing technique entitles this technique quite meet to
fabricate the tissue engineering material. However, confined by the
limited biocompatibility of photosensitive resin, it is difficult to employ
the photocuring 3D printing technique in the biomedical field at pre-
sent. It requires the innovation and mutual collaboration of both
printing technique and material. For example, commonly, in the pre-
sent, the hydrogel is printed by the injection printing for the low
strength of the hydrogel. The printed hydrogel is of low precision and
rough surface. Some tough hydrogels have been developed; however, it
requires high intensity and short wavelength of light. Meanwhile, to
print the hydrogel, the printing space of 3D printing machine should be
kept constant temperature and humidity to prevent moisture volatili-
zation. Brief summary, photocuring 3D printing has a promising future
in biomaterials, but it still needs to overcome the difficulties in tech-
nology and materials.

4. The existing problems and challenges of photocuring 3D
printing

It is known that the photocuring 3D printing was developed ini-
tially, however, its market share in 3D printing is relatively low at pre-
sent. The main reason is that the performance of material printed by
photocuring 3D technique is weak and the printed objects cannot be
directly used as structural parts. Generally, the performances of mate-
rials which are printed by photocuring 3D printing technique are
brittle, poor toughness. These materials can’t withstand impact. In ad-
dition, the poor biocompatibility of the photocuring 3D printing ma-
terials also limits its application in bioengineering materials. Currently,
the photocuring 3D printing materials are mainly used as temporary
materials, such as lost wax material, model, prototype design and so on,
which greatly limits the promotion and usage of the technology. Why
does this happen? It may be discussed from the materials and 3D
printing technique as following.

4.1. Problems and challenges of photosensitive resins

4.1.1. Lack of photosensitive resin with high performance and low viscosity

Currently, one common feature of all photocuring 3D printing
technologies is that the photosensitive resin should have low viscosity
or good fluidity. As we know, the resin with low viscosity is of small
molecular weight, which induces the photocured materials with high
crosslinking degree, further, leads the material hard and brittle. But if
the molecular weight of photosensitive resin is large, the viscosity is
very high. In order to be printable, it needs a lot of monomer to dilute,
which causes the loss of good performance of the resin. This contra-
diction between the viscosity and the performance of the resin is dif-
cult to be solved with present photocuring 3D printing. Therefore, the
development of photosensitive resin with low viscosity and high per-
fomance is very necessary.

4.1.2. Difficult to print the photosensitive resin with high viscosity

Many photosensitive resins with high viscosity have good elasticity,
toughness or other excellent properties. However, because the current
printing technology cannot print high-viscosity resins, the properties of
photopolymerization 3D printing materials are greatly limited. Therefore, development of technique to print high viscosity resin is
currently important.

4.1.3. Printing without support pillars

Photopolymerization 3D printing is a process of transforming liquid
resin into solid samples. During 3D printing, liquid resin cannot support
the operation, therefore, adding support pillars is necessary to ensure
the smooth printing process. However, removing the support pillars via
manual is a time-consuming process. At present, the 3D printing process
can be automated, but it still relies on manual to remove the support
pillars, which adds a lot of labor costs to the 3D printing technique.
Moreover, after removing the support column, the roughness of the
surface increases, the step of polishing is inevitable. Therefore, to de-
develop the support-free photopolymerization 3D printing is another re-
search direction.

4.1.4. Development of photopolymerizable degradable resin

Since currently photocuring 3D printing objects can only be used as
temporary materials, we can imagine that these materials will be dis-
carded after a short period of usage, which would cause serious en-
vironmental pollution. However, photocuring 3D printing materials are
highly crosslinked and cannot be directly recycled. Therefore, it is of
great significance to develop photopolymerizable 3D printing materials
with degradability.

4.1.5. Photocuring 3D printing biocompatible materials

3D printing is the best way to achieve personalized manufacturing,
which matches the characteristic of biological tissue. Photopolymerization 3D printing, which has high printing precision
and high speed, will have a very good application prospect in biological
tissue. However, the biocompatibility of materials is very important for
biomaterials. Thus, it is important to develop biocompatible materials
for photopolymerization 3D printing [31].

4.2. Problems and challenges of photocuring 3D printing technique

The research and development of 3D printing technology cannot be
separated from materials, the characteristics of materials should be
fully considered. At present, photocuring 3D printing has not yet make
breakthroughs in these areas: (1) the printing size of DLP, LCD tech-
nique is small; (2) the light intensity of LCD is weak which cause the
long printing time and low conversion degree; (3) the printing size of
SLA technique is large, but the printing efficiency is low; (4) photo-
curing 3D printing resin with high viscosity; (5) there is no standard of
the photocuring 3D printing technique; If the above problems can be
solved, great progress will be made in photocuring 3D printing tech-
nology, which will broaden the application of photocuring 3D printing
[32].

5. Summary and prospect

As a model-free manufacturing technology, photocuring 3D printing
with high printing speed and high precision is a very important 3D
printing technique. However, the limited performance of the photo-
sensitive resin and the bottlenecks of 3D printing technology restrict the
application of photocuring 3D printing. Once the technical problems
such as rapid curing, large size and high viscosity resin printing was
solved, as well as the development of high-performance materials,
biocompatible materials and degradable materials, the photocuring 3D
printing will have a broad prospect.

Author contribution

Xiaoqun zhu: Conceptualization, Formal analysis, Writing - review
and editing. Jun Nie: Funding acquisition, Supervision. Haoyuan Quan,
Ting Zhang, Hang Xu, Shen Luo: Writing - original draft.
Acknowledgements

This study was financially supported by the National Key Research and Development Program of China (2017YFB0307900) and the National Natural Science Foundation of China (No.51873008, 51603007). The authors also appreciate the support of the Beijing Laboratory of Biomedical Materials.

References

[1] Y.W. Tay, B. Panda, S.C. Paul, M.J. Tan, S. Qian, K.F. Leong, C.K. Chua, Processing and mechanical properties of construction materials for 3D printing, Mater. Sci. Forum 861 (2016) 177–181, https://doi.org/10.4028/www.scientific.net/MSF.861.177.

[2] Home shop 3D printing, 3D printing process and technologies, http://homeshop3dprinting.com/3d-printing/q-3d-printing-process-and-technologies/2017, Accessed date: 21 July 2019.

[3] 3D printing, http://en.wikipedia.org/wiki/3D_printing, (2019), Accessed date: 5 July 2019.

[4] M. Umar, S.K. Wan, An Online 3D Printing Portal for General and Medical Fields, International Conference on Computational Intelligence & Communication Networks, Jabalpur, India, 2016-08-18 https://ieeexplore.ieee.org/document/7546998.

[5] F. Yang, Y.K. Yang, H. Zheng, Application of 3D printing in diagnosis and treatment of congenital heart disease, Chin. J. Interventional Imaging Ther. 11 (2014) 629-631 http://en.cnki.com.cn/Article_en/CJFDTOTAL-JRYX201409032.html.

[6] M. Kroher, Morphological chimeras of larvae and adults in a hydrozoan–insect into the control of pattern formation and morphogenesis, Int. J. Dev. Biol. 44 (2000) 861-866 http://www.ncbi.nlm.nih.gov/pubmed/11206327.

[7] J. Wang, A. Goyanes, A.W. Basit, Stereolithographic (SLA) 3D printing of oral modified-release dosage forms, Int. J. Pharm. 503 (2016) 207–212, https://doi.org/10.1016/j.ijpharm.2016.03.016.

[8] A. Melisiris, T. Pang, W. Renyi, Liquid, radiation-curable composition, especially for producing flexible cured articles by stereolithography, US20020177073A1. 2002-11-28, https://patents.google.com/patent/US20020177073A1/en?oq=

[9] F.P. Jacobs, Stereolithography and Other RP&M Technologies-From Rapid Prototyping to Rapid Tooling, Society of Manufacturing Engineers Dearborn, MI, USA, 1996.

[10] J.V. Crivello, UV and electron beam-induced cationic polymerization, Nucl. Instrum. Methods Phys. Res. 151 (1999) 8-21, https://doi.org/10.1016/S0168-9002(ad03)00109-3.

[11] J. Wang, A. Goyanes, S. Gaisford, A.W. Basit, Stereolithographic (SLA) 3D printing of oral modified-release dosage forms, Int. J. Pharm. 503 (2016) 207–212, https://doi.org/10.1016/j.ijpharm.2016.03.016.

[12] Y.H. Cho, I.H. Lee, D.W. Cho, Laser scanning path generation considering photo-polymer solidification in micro-stereolithography, J. Microscyt. Technol. 11 (2005) 158-167, https://doi.org/10.1007/s00542-004-0468-2.

[13] M. Asif, X. Sun, New 3D Printing Technique Using Extrusion of Photopolymer, Twenty Fifth International Conference on Process and Fabrication of Advanced Materials, At University of Auckland, New Zealand, 2017-01.

[14] M.F. James, A.Y. Lars, Display system architectures for digital micromirror device (DMD)-based projectors. Proc. SPIE Int. Soc. Opt. Eng. 2650 (1996) 193-208, https://doi.org/10.1117/12.237904.

[15] R. Mainur, Statistical Analysis of the Digital Micromirror Devices Hinge Sag Phenomenon, Masters-Granting, Texas Tech University, La Berk, Texas, USA, 2002-05http://hdl.handle.net/2346/17048.

[16] J. Wang, Y. Liu, X. Qian, X. Ma, Effect of organic dyes on DLP-3D printing photosensitive resin, Chem. Reagents 40 (2018) 528–532 http://en.cnki.com.cn/Article_en/CJFDTOTAL-HSJS201806007.htm.

[17] L. Wu, L. Zhao, M. Jian, Y. Mao, M. Yu, X. Guo, EBM-DLP, multi-projector DLP with energy homogenization for large-size 3D printing, Rapid Prototyp. J. 24 (2018) 1500–1510, https://doi.org/10.1108/RPJ-04-2017-0060.

[18] J. Veligdan, C. Biscardi, C. Brewster, L. Reiser, L. DeSanto, Physicall optical display, Aerosense 97, Orlando, FL, United States, 1997-07-01 https://doi.org/10.1117/12.277012.

[19] D.G. Chang, S.M. Li, C.F. An, The influence analysis of globular indexing cam mechanism size parameters on transmission performance, Adv. Mater. Res. 426 (2012) 163-167, https://doi.org/10.4028/www.scientific.net/AMR.426.163.

[20] M. Ishii, T. Kawamura, H. Yamate, M. Takabatake, Liquid crystal display, US9334000B1. 2015-05-28, http://www.freepatentonline.com/6934000.html.

[21] L. Wu, L. Zhao, M. Jian, Y. Mao, X. Guo, EBM-DLP: multi-projector DLP with energy homogenization for large-size 3D printing, Rapid Prototyp. J. 24 (2018) 1500–1510, https://doi.org/10.1108/RPJ-04-2017-0060.

[22] J.R. Turnbull, D. Shrivanyants, N. Ermoshkin, R. Janasziewicz, A.R. Johnson, D. Kelly, K. Chen, R. Pinschmidt, J.P. Rolland, A. Ermoshkin, E.F. Samuaki, J.M. DeSimone, Continuous liquid interface production of 3D objects, Science 347 (2015) 1349–1352, https://doi.org/10.1126/science.aaa2397.

[23] J. Balli, S. Kumpaty, V. Annewasser, Continuous Liquid Interface Production of 3D Objects: an Unconventional Technology and its Challenges and Opportunities, Asme International Mechanical Engineering Congress & Exposition, Tampa, Florida, USA, 2017-09-03.

[24] M. Šerčer, T. Rezic, D. Godic, D. Oros, Microreactor production by PolyJet matrix 3D-printing technology: hydrodynamic characterization, Food Technol. Biotechnol. 57 (2019) 272–281, https://doi.org/10.11711/bt.57.02.19.5725.

[25] X. Cui, K. Breitenkamp, M.G. Finn, M. Lotz, Darryl D. D’ Lima, Direct human cartilage repair using three-dimensional bioprinting technology, Tissue Eng. A 18 (2012) 1304–1312, https://doi.org/10.1089/ten.tea.2011.0543.

[26] J.H. Park, J. Jang, J.S. Lee, D.W. Cho, Three-dimensional printing of tissue/organ analogues containing living cells, Ann. Biomed. Eng. 45 (2017) 180–194, https://doi.org/10.1007/s10439-016-1161-9.

[27] P.E. Petrochenko, J. Torgersen, P. Gruber, L.A. Hicks, J. Zheng, G. Kumar, R.J. Narayan, P.L. Goering, R. Liska, J. Stampfl, A. Ovsiansko, Laser 3D printing with sub-microscale resolution of porous elastomeric scaffolds for supporting human bone cells, Adv. Healthc. Mater. 4 (2015) 739–747, https://doi.org/10.1002/adhm.201400442.

[28] P. Danilevičius, L. Gregogiadi, C.J. Pateman, F. Claeyssens, M. Chatzinikolaidou, M. Farsari, The effect of porosity on cell ingrowth into accurately defined, laser-made, polylactic-based 3D scaffolds, Appl. Surf. Sci. 336 (2015) 2–10, https://doi.org/10.1016/j.apsusc.2014.06.012.

[29] S. Hong, D. Sycks, H.F. Chan, et al., 3D Printing of highly stretchable and tough hydrogels into complex, cellularized structures, Adv. Mater. 27 (2015) 281, https://doi.org/10.1002/admt.201400442.

[30] Z. Wang, R. Abdulla, B. Parker, et al., Asimple and high-resolution stereolithography-based 3D bioprinting system using visible light crosslinkable bioinks, Biofabrication 7 (4) (2015) 045009.

[31] Z. Wang, R. Abdulla, B. Parker, et al., Asimple and high-resolution stereolithography-based 3D bioprinting system using visible light crosslinkable bioinks, Biofabrication 7 (4) (2015) 045009.