A Glance at the recent additive manufacturing research and development in China

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Abstract

This paper reviews some of the recent additive manufacturing research and development works in China. A considerable amount of AM research activities in China focuses on directed energy deposition processes, powder bed fusion processes and stereolithography, with much of the effect dedicated to system and application development. Although many of the recent results are not readily available from the literatures published in China, from the available information the areas of focus for research and development could be clearly seen. Despite some speculations, the AM research in China is vibrate and aggressive, with some areas at least several years ahead of the other countries.

1. Introduction

China is among the earliest countries that started additive manufacturing (AM) research. Back in around 1990, several groups in China had started AM various AM research efforts, which include Tsinghua university (led by Dr. Yongnian Yan), Huazhong University of Science and Technology (led by Dr. Yungan Wang) and Xi'an Jiao Tong University (led by Dr. Binheng Lu). After over 20 years, the AM research in China has greatly expanded into a wide range of areas from aerospace, defense, automobile, biomedicine to appliance, tooling, micro/nano-fabrication and art design. Currently there exist over 10 large research groups and companies in China that have been extensively involved in AM research, which include Northwestern Polytechnical University, Beihang University, South China University of Technology, Nanjing University of Aeronautics and Astronautics, University of Science and Technology of China, Shanghai Jiao Tong University, Northwest Institute for Nonferrous Metal Research, China Academy of Engineering Physics and Beijing Longyuan beside the other three mentioned previously. Unlike some of the other countries such as U.S. and U.K., most of the research institutes in China also own their companies that sell their own systems and provide AM services. Therefore, one of the unique characteristics of AM research in China is that a significant portion of research efforts is dedicated to the system integration including both hardware and software. On the other hand, the AM market in China is still largely focused on a few high value-added applications, while the overall manufacturing market as well as the personal desktop printer market largely untapped.

Likely due to the market demands, several AM processes including stereolithography (SLA), powder bed fusion (PBF) and directed energy deposition (DED) have seen quite considerable development in China in the recent years. For example, China is among the most advanced countries in the use of directed energy deposition technologies in the manufacturing of large aerospace components. On the other hand, some of these achievements are largely unfamiliar to the researchers outside of China. Therefore, in this paper, we attempt to review some of these works that have been published in various Chinese science and engineering journals. Although many of these publications did not offer sufficient technical details about certain works, overall some general observations can be made for the process/material development and applications. Also, as research areas such as bio-printing and organ printing represent a rather unique branch of AM, these works were not within the scope of this review despite the fact that extensive research has been performed.

2. Stereolithography (SLA)

Multiple research groups in China started research works related to SLA back in early 1990s. Recently, more application oriented research works were performed by groups such as Xi'an Jiao Tong University by Dr. Binheng Lu and Dr. Dichen Li. On the other hand, relatively limited works are focused on new photopolymer development [1,2].

2.1 Equipment

A lot of the research was focused on the development of new light source and the improvement of process accuracy. Several groups explored the use of non-laser UV light source in SLA systems including mercury-xenon UV lamp [3, 4, 5] and UV-LED [6]. Mercury-xenon UV lamp was used as a low-cost substitute of the traditional UV laser sources, however suffers from low coherence, which requires additional optical manipulations [3, 4]. Jun et al. reported the development of a SLA system with LED as energy source, which could achieve a stable output power of over 30mW and a beam diameter of about 0.3mm [6]. Wu et al. suggested that the LED UV SLA system could result in significant cost saving as well as an energy saving of over 99%, although currently it also suffers the disadvantage of lower energy density and coarser beam size [4]. In the effort of improving control and fabrication accuracy, various techniques were studied by multiple groups, including the laser based resin position measurement [7], surface-constrained recoating [8], and resin compensation [9], which were implemented in different commercial systems. Various commercial SLA systems are available from companies such as Shanxi Hengtong and Beijing Yinghua, which are capable of fabricating photopolymer and ceramic parts with a layer thickness of 0.04mm and accuracy of 0.08mm [10], although layer thickness of 0.01-0.02mm was also reported for research systems [8]. In addition, Shanxi Hengtong also released their digital light projection (DLP) based SLA system. Fig.1 shows some of the SLA systems developed by the same company.

a. SCPS350B (DLP based)

b. SPS600

c. SPS250M (medical grade)

d. SPS350C (ceramic)

Fig.1 SLA systems from Shanxi Hengtong

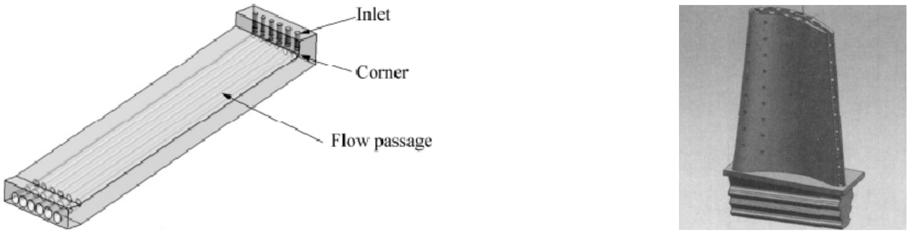
2.2 Process development

A considerable portion of the researches related to the SLA process in China focuses on the accuracy improvement, which approach the problem from various aspects such as scanning strategy [11-15], support generation [16] and residual stress reduction [17]. As many research groups develop their own SLA systems and therefore have full control of all process parameters, some interesting process strategies were investigated. For example, Lei et al. combined the double-scanning curing strategy with the scanning area sectioning in order to reduce warping of overhanging structures, which showed significant improvement compared to both the original double-scanning strategy and the STAR-WEAVE strategy [11]. The same group also suggested that the proper design of sectioning and section scanning strategy based on the curing characteristic of the photopolymer could along potentially result in significant reduction of part warping and improvement of part quality [17]. In another work, through experimental based process optimization, Xiang et al. reported the successful fabrication of micro-gears with minimum feature size of about 70μm using standard SLA system [18]. Hong et al. developed an algorithm that recognizes different types of overhanging structure and generates support structures accordingly, which was implemented into the commercial systems by Shanxi Hengtong [16]. In addition, The group at Xi'an Jiao Tong University also performed extensive research works on the material and process development of specific systems, such as the investigation of time-dependent curing profile evolution for ceramic particle loaded photopolymer and regular photopolymer with mercury-xenon UV source utilizing both experimentation and molecular dynamics simulation using Monte Carlo method [15, 19].

Due to the conflict of commercial interest between different research institutes, much of the process/material development research works published in China represent independent but often overlapping efforts with same problems. In general, due to the focus on commercialization as well as the relatively mature level of technological development, there exist limited recent research works in China that focus on the process/material development of SLA.

2.3 Applications

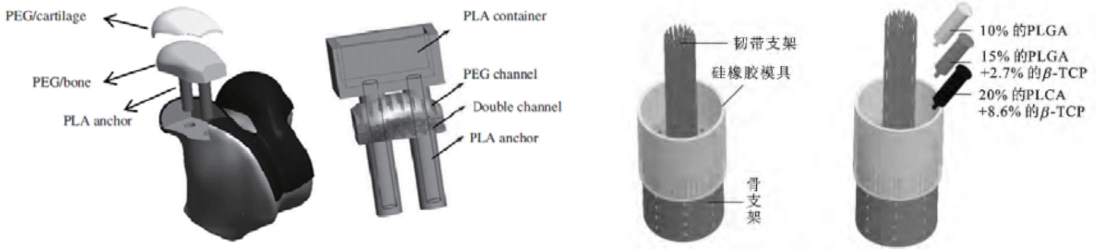
With the rapid development of biomedical and aerospace industries in China, various studies have investigated the use of SLA for these applications, especially for those with stringent requirements with geometrical accuracies. Xi'an Jiao Tong University has worked extensively on the fabrication of wind tunnel and ceramic turbine blades using SLA as either direct or indirect methods, as shown in Fig.2 [20-23]. Due to the limitation of material strength, the application of SLA in aerospace areas primarily focuses on the fabrication of molds and patterns that are subsequently used for investment casting. The parts fabricated by SLA could either be used directly as pattern for casting or as shells that can be reinforced by metal-resin composites to serve as the mold for wax pattern casting [24-26]. This type of processes was studied in various works in details using either finite element simulation or experimentation, which reported the resulting alleviation of thermal residual stress due to the casting process and the elimination of thermal cracks [25, 26].



a. Wind tunnel [22] b. Turbine blade [23]

Fig.2 SLA applications in aerospace

In biomedical areas, extensive studies have been performed in various applications utilizing SLA, which is led by the group in Xi'an Jiao Tong University. These works primarily focused on the fabrication of scaffolds for soft tissue regeneration or for hard tissue implantation [27-34]. Zhuang et al. developed a three-step process for the fabrication of PEG (polyethylene glycol)/ PLA (polylactide)/β-TCP (tricalcium phosphate) composite bone/cartilage joint scaffold shown in Fig.3 [30, 31]. The β-TCP structure was realized from the pattern fabricated by SLA, the PLA anchor structure was fabricated by weaving PLA fibers that mimic the ligaments, and the PEG cartilage was fabricated directly by SLA. This hybrid manufacturing method was also applied to fabricate ligament-bone composite scaffold [33] and magnesium-ceramic composite bone scaffold [34], which generally resulted in improved biological and biomechanical responses in both in-vivo and clinical experiments. For hard tissue prostheses, using SLA parts as investment casting pattern, Yaxiong et al. have implemented custom AM titanium implants in more than 100 clinical trials [28]. Overall the adoption of AM in biomedical applications has been significantly more aggressive than most other countries including U.S., which can be expected to serve as a critical advantage for the development of this technology in the long term.



a. Large joint scaffold [30] b. Ligament-bone scaffold [31, 35]

Fig.3 Composite scaffold via SLA

3. Powder bed fusion (PBF)

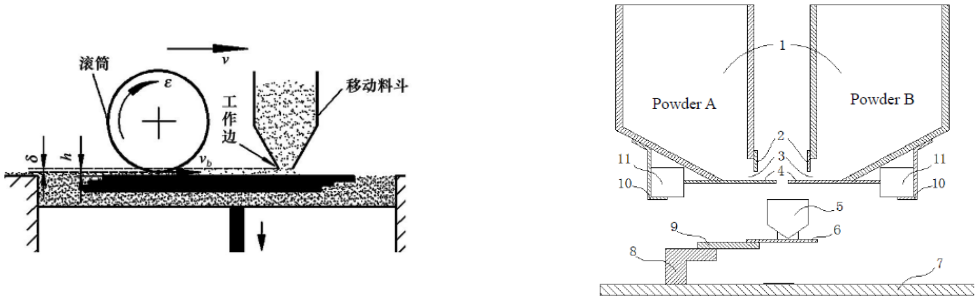
Various groups in China have been extensively involved in PBF related research, which include Tsinghua University, Northwest Institute for Nonferrous Metal Research, South China University of Technology, Huazhong University of Science and Technology and Nanjing University of Aeronautics and Astronautics. Most of these research groups have developed their own PBF systems, such as the EBSM-150 electron beam PBF from Tsinghua University, DiMetal-240/280/100 laser melting PBF from South China University of Technology, RAP-1 laser PBF from

Nanjing University of Aeronautics and Astronautics, and various laser polymer PBF systems from Huazhong University of Science and Technology.

3.1 Equipment

3.1.1 Electron beam melting systems

Tsinghua University developed its first electron beam based PBF system named electron beam selective melting (EBSM) around 2004, which was among the first research groups that independently developed such type of systems [36]. The research group led by Dr. Feng Lin has performed extensive research with the EBSM system including powder spreading, powder preheat and scanning control. The prototype system utilizes a hopper-roller powder spread mechanism as shown in Fig.4a [37], which was later replaced by a vibration based powder spread mechanism that could achieve minimum layer thickness of 0.1mm via closed-loop powder weight control [38]. Recently, Chao et al. further developed a vibration based dual-powder spread system as shown in Fig.4b, which could realize the controlled mixing of two powders [39]. It was suggested that this new mechanism could realize more efficient fabrication of digital materials and functionally graded materials. In addition, the same group has also demonstrated the successful spread of titanium powder with very low flowability and spreadability that were non-printable via traditional powder spread mechanism. Furthermore, a tilted comb spreader was also designed for the EBSM system, which could reduce shear stress exerted on the fabricated parts during the powder spreading [39]. Beside this group, multiple other groups also performed extensive research on platform development [40, 41]. The selective electron beam (SEBM) S1 system developed by Northwest Institute for Nonferrous Metal Research was reported to have layer thickness of 50-200µm, beam size 200µm, scanning speed of 8km/s, material melting speed 10-100m/s and fabrication accuracy of 1mm [40]. Overall these systems still lack the level of system integration and process accuracy of the commercial electron beam system by Arcam. However, due to their open architecture hardware and software, these systems are currently sought after as research platforms for new material development with electron beam energy sources.



a. Hopper-roller system b. Vibration based dual-powder system

Fig.4 Powder spread mechanism in EBSM

3.1.2 Laser melting systems

South China University of Technology was among the first groups in China to develop laser melting PBF systems, and some of their systems are shown in Fig.5. Led by Dr. Yongqiang Yang, this research group also performed extensive research on the material development using their in-house laser melting systems, which will be introduced in the following section [42, 43]. Huazhong University of Science and Technology also developed their own HRPM-II laser melting PBF system, and performed extensive research works in the improvement of laser deflection and focusing mechanisms using various approaches [44-46]. It was reported that the HRPM-II system has a positioning repeatability of 30µm and scanning accuracy of 0.1mm/100mm [46].

a. DiMetal-240 b. DiMetal-280 c. DiMetal-100

Fig.5 DiMetal laser melting systems

3.1.3 Laser sintering systems

Huzhong University of Science and Technology is among the earliest groups in China that developed polymer laser sintering PBF systems [47-49]. Wuhan Binhu Mechanical & Electrical Co. Ltd, which is affiliated to the university, currently offers at least six different models of laser sintering systems, which include the largest HRPS-VIII system with build envelop of 1400x1400x500mm, layer thickness of 0.08-0.3mm and part accuracy of 0.2mm/200mm [50]. Recently, the Changsha based Farsoon also started to provide laser sintering solutions from equipment to material supply [51]. By collaborating with BASF, Farsoon is also developing new polymer materials suitable for laser sintering PBF, although no further details are currently available. Fig.6 shows some of the commercial laser sintering PBF systems developed in China.

a. HRPS-III b. Farsoon 402

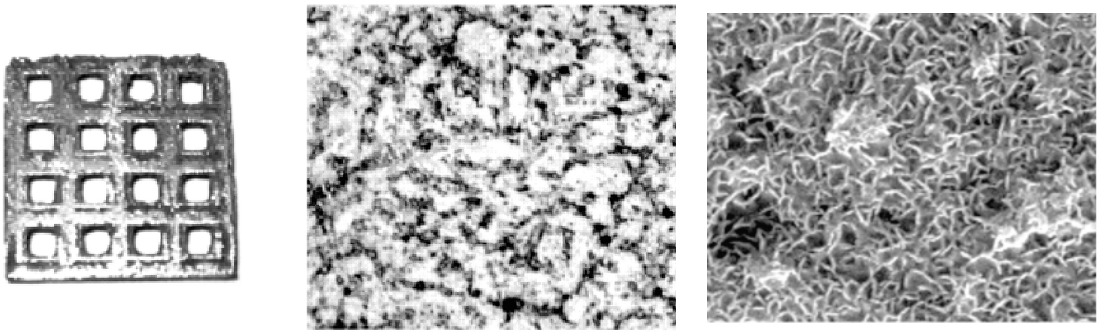
c. Lasercore-7000 d. MEM450A

Fig.6 Laser sintering PBF systems in China

3.2 Process development

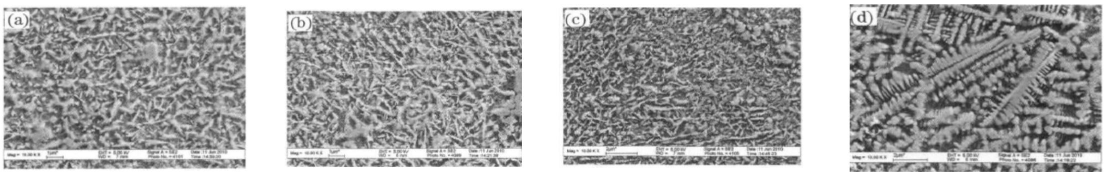
For electron beam PBF, extensive works have been carried out in the investigation of relationships between scanning strategies and the microstructure and properties of the fabricated parts. Qi et al. developed a kinematic model for the powder bed, which was subsequently used for the design of vacuum system in the EBSM system and the optimization of preheat strategies [52]. In another work, He et al. proposed an electron beam preheat strategy, which gradually increases the preheating electron beam current in order to realize preheat of Ti6Al4V powder with relatively low electrical conductivity [53]. In addition, it was also suggested that the pre-sintering effect could help reduce the tendency of balling during the melting process [53]. Several studies investigated the effect of powder mixing on their processibility, and concluded that when the mixing ratio between the more spherical gas atomized powder and the irregular water atomized powder is around 40%:60%, the powder bed exhibits highest processibility with both preheating and melting [54, 55]. In a recent work, Guo et al. studied the relationship between the input energy density and the surface texture of the 316L stainless steel fabricated via EBSM, and proposed a two-step process strategy that aimed to improve the surface finish of each newly fabricated layer [56]. The proposed method utilizes low energy density scanning to introduce partial melting in the fabricated layer, which is followed by a subsequent re-melting with higher energy density. It was reported that this approach potentially allows for more sufficient melting pool evolution by forming large-size melting pools, which resulted in a top surface finish of less than 8μm, as well as 99.96% density with microstructure dominated by refined columnar and equiaxial grains [56].

For metal laser melting PBF, extensive studies have been carried out by various groups that focus on the process-microstructure-property relationships of the laser melting PBF systems using various materials including 316L stainless steel, CoCrMo alloys, 304 stainless steel and Inconel 718 alloy [57-70]. Wu et al. developed a core-shell process strategy for the rapid fabrication of 316L stainless steel parts with fully dense shell and porous cores. Using the laser laser power (85W), higher scanning speed and larger scanning spacing (700mm/s and 0.08mm, respectively) were used for the core fabrication, while lower scanning speed and smaller scanning spacing (300mm/s and 0.06mm, respectively) were used for the skin fabrication. It was reported that this approach helped reducing the thermal distortion of the fabricated parts by about 75% and process time by about 25% [60]. Song et al. studied the effect of laser process parameters (power, scanning speed and spacing) on the mechanical properties of the CoCrMo alloy, and it was reported that the higher yield strength, ultimate strength as well as hardness of the as-fabricated parts were superior compared to the ASTM F75 specifications, while the elongation was significantly lower [61]. Lu et al. studied the in-situ alloying and fabrication of Fe-8Ni-0.5C alloy from pre-mixed elemental powder [65]. The process parameters were optimized through single-layer study, and a metal lattice part as shown in Fig.7a was successfully fabricated with 22A power, 45mm/s scanning speed, 0.07mm spacing and layer thickness of 0.18mm. Subsequent microscopy observed predominantly needle-shaped martensite in the microstructure as well as some retained austenite as shown in Fig.7b-c, while no significant element segregation was reported [65]. Zhang et al. compared the process parameters of a series of aluminum alloys including AlSi25, AlSi10mg, AlMg5 and AlMgSi0.5, and analyzed the mechanisms of internal porosity generations [66]. It was suggested that at least two porosity generation mechanism exist. When the input energy is insufficient, internal porosity could form due to the lack of fusion. On the other hand, when excessive input energy is used, the evaporation of magnesium contributes to the formation of small spherical porosities, which also result in the change of overall material compositions. The group at Nanjing University of Aeronautics and Astronautics led by Dr. Dongdong Gu has also performed extensive research with the process development for various materials including Inconel 718 and various metal matrix composite materials. Ying et al. studied the influence of input energy density to the solidification characteristics of the molten material [71]. It was found that at low input energy density, the microstructure of the IN718 parts fabricated by laser melting PBF exhibit large columnar γ grains with large cracks within these grains as well as small grains at the grain boundaries. In addition, there also exists significant epitaph growth in the structure. As the input energy density increases, the IN718 microstructure start to exhibit more aligned columnar grains with less epitaph growth and refined grain size [71]. Meng et al. studied the fabrication of TiC reinforced Titanium matrix composite structure using laser melting PBF [67]. Using pre-mixed TiC-Ti powder, the group investigated the effect of different processing parameters on the density and defects of the fabricated parts, and discussed the mechanism for the existence of an optimum input energy density. As shown in Fig.8, the microstructure of the TiC-Ti composite exhibit homogeneous microstructure with nano-size TiC phase dispersed within the Ti matrix until the energy density becomes excessive, at which point the microstructure becomes large dendrite with large grain sizes [67]. The same group also performed some very interesting studies with the process of non-traditional materials and structures, such as the modeling of the melting pool dynamics for W-Cu dual-material system with tungsten particles remain solid during the melting process [68], as well as the use of foaming agent in the direct laser fabrication of 316L stainless steel with honeycomb porosities as shown in Fig.9 [69].



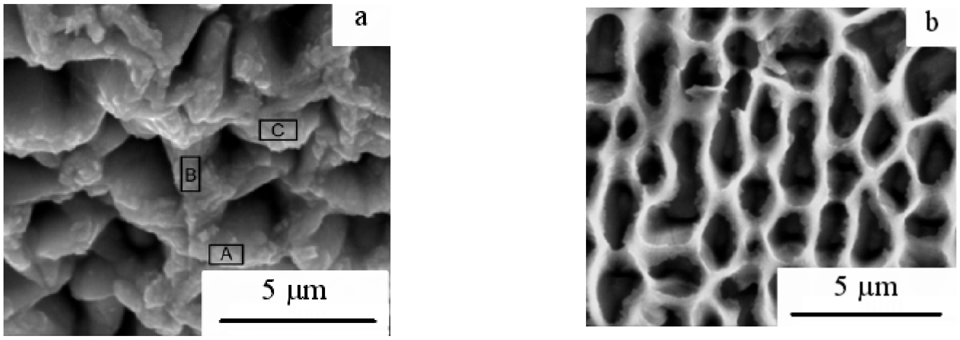
a. Fabricated part b. Microstructure 1000x c. Microstructure 10000x

Fig.7 Fe-Ni-C parts by laser melting system via in-situ alloying [65]



a. 200J/m b. 267J/m c. 400J/m d. 800J/m

Fig.8 Microstructure of TiC/C composite under different energy densities [67]



a. Surface b. Cross-section

Fig.9 316L stainless steel with honeycomb porosity fabricated by laser melting PBF [69]

The research group in Huazhong University of Science and Technology led by Dr. Yusheng Shi have performed systematic research with polymer laser sintering processes, while some of the other research groups focused more on non-traditional sintering materials. Recently, Yan et al. studied the sintering phenomenon during the laser sintering process with several different materials, which found that the undesired secondary sintering between the processed region and the surrounding areas could be reduced by adding inorganic filler materials with high melting temperature [72]. It was also suggested that the secondary sintering is more significant for polymers with higher degree of crystallinity [73]. As it is widely known that current laser sintering process has considerable degree of uncertainty in process control. In an attempt to address this issue, Liu et al. explored the feasibility of implementing neural network based control algorithm for the process control optimization, although the authors did not find further works that verify its efficiency [74]. The same group also developed a hybrid process that combines laser sintering with hot isostatic pressing (HIP), in which the laser sintered parts were used as the pattern for HIP mold, and the HIP was used as the primary shape generation process [75]. This approach overcomes some of the limitations of the laser sintering process in the manufacturing of metal parts, and was demonstrated to be capable of producing high strength AlSi316L parts with complex geometry as shown in Fig.10.

Fig.10 Complext AlSi316L parts fabricated by SLS/HIP

3.3 Applications

Despite the extensive research, currently there exist relatively limited applications for metal PBF processes in China. Various groups have demonstrated the capability of PBF in the direct fabrication of metal structures and components in a range of applications including orthopedics [76, 77], surgical devices [78], complex mechanical joints [79], turbine engine plates [80] and emboss sculpture [81]. However, only a few areas that have high demand of high value-added metal components have adopted metal PBF processes, such as aerospace and orthopedics. On the other hand, the polymer and non-metal PBF processes have been widely used in tooling industries to fabricate wax patterns, sand cores and even direct tooling for a range of industries including automobile and aerospace [82, 83]. Fig.11 shows a pair of casting mold for an engine block of 2000mmx1000mmx450mm in size fabricated by laser sintering process, with each half of the mold assembled from two pieces [83].

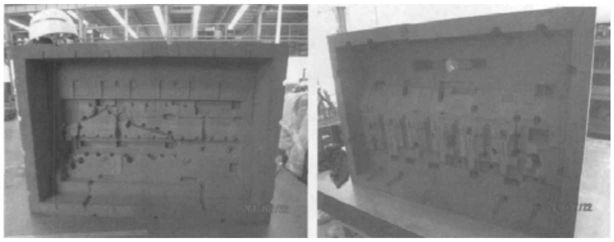


Fig.11 Engine block mold by laser sintering, left is drag and right is cope

4. Directed energy deposition (DED)

One of the most rapidly advancing AM areas in China is the DED, which has started to receive considerable attentions worldwide. Started in late 1990s, various groups in China have worked extensively on this type of processes, with research almost exclusively focused on the process-microstructure-property studies with various aerospace materials using laser based systems. Currently the two leading research institutes are Northwestern Polytechnical University and Beihang University, which have collaborated with defense agencies and independently demonstrated the fabrication of large titanium aerospace components using in-house developed laser DED systems.

4.1 Equipment

There currently exist several commercial laser DED systems in China, which are mostly developed by owned Xi’an Bright Ltd that is owned by Northwestern Polytechnical University. Until 2012, this group has developed various laser DED systems that use CO2 laser, Nd:YAG laser, fiber laser and diode laser as energy sources depending on their applications, and have sold multiple of these equipment to Chinese aerospace companies as well as GE China Research Center. These systems can achieve atmospheric control of O_2<10ppm and possess real-time closed-loop feedback control systems based on melting pool temperature, melting pool size and layer height [84]. Fig.12 shows two of the systems developed by Bright. Recently, Beihang University also found a commercial company that starts to offer laser DED equipment [85].

a. LSF-V b. LSF-IV

Fig.12 Laser DED by Xi’an Bright [84, 86]

4.2 Process development

The research group in Northwestern Polytechnical University led by Dr. Weidong Huang focus extensively on the solidification process and microstructural control during the laser DED processes. As part of the State Key Laboratory of Solidification Processing, this research group has developed relatively comprehensive expertise on the fabrication of large metal components with controlled thermal stress and microstructure. Starting from 1998, the research group in Beihang University as part of the Engineering Research Center of Ministry of Education on Laser Direct Manufacturing for Large Metallic Component led by Dr. Huaming Wang have also performed extensive research works on the development of process parameters of various aerospace alloys including titanium alloys, Ni-superalloys, Fe-superalloys, high strength steels and intermetallics, as well as their post heat treatment processes for improved microstructural and performance control.

Various literature works are available for the process development of various titanium alloys using laser DED, including TC2 (Grade 3), TC4 (Ti6Al4V), TC17 (Ti-5Al-2Sn-2Zr-4Mo-4Cr) and TC18 (Ti-5Al-4.75Mo-4.75V-1Cr-1Fe) [87-101], as well as the in-situ alloying study of Ti-xAl-yV (X<11, Y<10) [102-104], TiB+TiC/TA15 and Ti-6Al-2Zr-Mo-V alloys [105-107]. Ma et al. developed a fractal scanning strategy, which helped to improve the temperature field homogeneity due to the self-similar pattern of the fractal scanning paths [108]. Combined with the partial laser beam offset strategy, this scanning method was reported to significantly improve the part quality by reducing insufficient fusion and internal porosity. In another study, in order to avoid non-uniform thermal dissipation characteristics in different part of the scanning area in each layer, Ma et al. also developed a geometrical style recognition based automatic scanning path generation and process parameter control [109]. For regions A and B as shown in Fig.13a, the automated algorithm generates different process parameters that reduces various manufacturing defects and improve the fabrication quality and accuracy for the direct manufacturing of the C919 aircraft wing chord shown in Fig.13b. Although no research literature was found by the authors, it was explicitly suggested that the fatigue and creep properties of the fabricated components are either comparable or better compared to the traditionally manufactured parts.

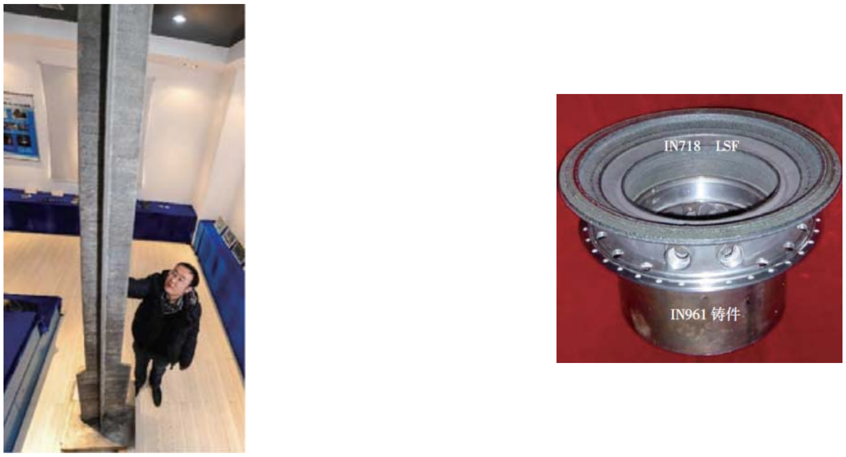
a. Geometrical style recognition b. aircraft wing chord

Fig.13 Geometry-based process adjustment of laser DED [109]

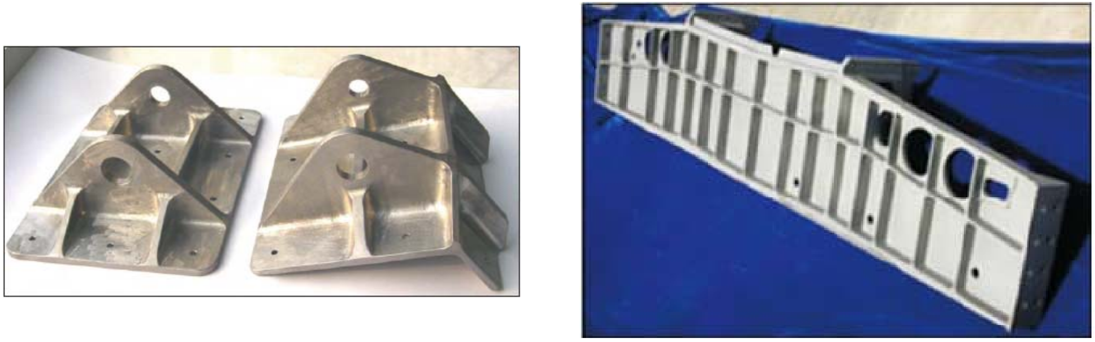
Extensive works have also been performed on the development of 17-4PH stainless steel for component repair [110-112]. It was reported that the microstructure of the 17-4PH fabricated by laser DED exhibit two types of martensite as well as precipitated secondary phases, which evolves into fine lath martensite with coarsened secondary phases during tempering [110, 111]. The same group also employed cellular automata in the modeling of solidification and dendrite growth [112], as well as epitaph growth on Fe-C single crystal substrate [113]. In the experimental investigation of the solidification behavior of laser DED process, Wang et al. utilized transparent butanedinitrile-2.0% ethanol alloy and realized real-time simulation of melting pool formation and non-equilibrium solidification that mimics the real laser DED process [114]. It was found that the solidification and microstructure are affected by the melting pool morphology as well as the grain orientation of the substrate. There also exist interesting works from the other research groups. For example, Wang et al. explored the use of ultrasonic vibration in laser DED fabrication of BT20 (Ti-6Al-1.5Mo-1.5V) alloy [115]. Using excitation frequency of 19.56kHz, it was found that the internal porosity and resulting grain size showed considerable improvement, however the deposition rate were also negatively affected. Pi et al. studied the self-stabilizing effect during the laser DED process that facilitates smooth finish, and proposed to employ process spacing at off-focus distance in order to utilize this effect [116]. Wang et al. studied the adjustment of powder delivery rate in order to improve the accuracy and surface quality of the tilted thin-wall structures [117].

4.3 Applications

Laser DED technologies have been adopted in various areas in China, including aerospace, biomedical, tooling, automobile and shipbuilding. One of the most widely reported applications is the direct fabrication of large aerospace components. Fig.14a shows a Ti6Al4V C919 aircraft wing chord with 450x350x3000mm size fabricated by Northwestern Technical University [118]. It was reported that the long-term dimensions stability of this part is smaller than 1mm without any post heat treatment. In addition, both the quasi-static and fatigue properties of the component are better than the wrought parts. Fig.14b shows a dual-alloy bearing case based on Ni-superalloy, which was fabricated with two material compositions in order to better accommodate the thermal characteristics between different parts of the aircraft engines [118]. Beihang University fabricated various aerospace components including corner case, fitting for aircraft seats (shown in Fig.14c), pelvic joints and other secondary titanium structural components, which have been installed in various models [119, 120]. It was reported that the material utilization was improved by 5 times, and the fabrication time and cost were reduced by 67% and 50% respectively. Recently this group also successfully fabricated large TA15 titanium part for main structural components in aircraft with overall dimension over 1730x250x230mm as shown in Fig.14d.



a. C919 wing chord [118] b. Bearing case [118]



c. Seat fitting [119] d. Large aircraft structural comonent [119]

Fig.14 Aircraft components fabricated by laser DED

Northwestern Polytechncial University has also been collaborating with the Fourth Military Medical University to fabricate dental prostheses using laser DED. As shown in Fig.15, it was expected that functionally graded structures with metal-hydroxylapatite graded material composition and varying porosity can be directly fabricated to accommodate both biological and mechanical requirements for the prostheses [121]. It was reported that this concept has been proved with multiple material combinations including stainless steel, CoMoCr alloys, titanium alloys and Ti/HA graded materials via preliminary clinical trial [121].

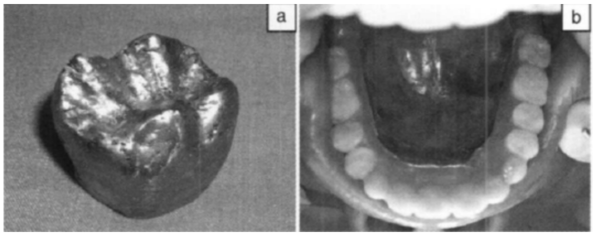


Fig.15 Dental crown and mandibular based plate by laser DED [121]

5. Conclusions

It was the impression of the authors that the AM research in China is highly aggregated in several major research institutes, which is partly contributed by the research resources that these institutes are capable of attracting. Almost all the research groups in China developed their own research systems, and some of these systems have been commercialized. In general, much of the equipment focused research between different groups exist significant overlap, which makes it difficult to grasp the most recent advancement of the technologies.

Many of the AM research works focus on application development, especially with the relatively well-developed AM processes such as stereolithography and powder bed fusion. On the other hand, several research groups in China have demonstrated extensive research expertise and achievement with both the fundamental process development and application development for the directed energy deposition processes. With aggressive adoption by aerospace and biomedical industries, the application of AM may experience a more rapid progress compared to most other countries.

There currently does not exist a research collaboration platform between U.S. and China. On the other hand, several mechanisms exist for the collaboration between Europe and China. There exist considerable potentials in collaborations between U.S. and China, which appear to have complementary expertise in many areas.

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