Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.jzus.zju.edu.cn; www.springerlink.com
E-mail: jzus@zju.edu.cn

Progress in selective laser melting equipment, related biomedical metallic materials and applications*

Yu-chao BAI, Fan FU, Ze-feng XIAO, Ming-kang ZHANG, Di WANG†‡,
Yong-qiang YANG, Chang-hui SONG
School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510640, China
†E-mail: mewdlaser@scut.edu.cn

Received Sept. 8, 2017; Revision accepted Dec. 27, 2017; Crosschecked Jan. 15, 2018

Abstract: This paper introduces the latest achievements of the South China University of Technology in basic research on selective laser melting (SLM), applications of SLM manufacturing equipment, and biomedical metallic materials manufactured by SLM. First, we describe the use of DiMetal-100 equipment to study the process parameters, microstructure, and mechanical properties of three kinds of metal medical materials manufactured by SLM, including 316L stainless steel, CoCrMo, and Ti6Al4V. Second, we describe the application of 316L stainless steel manufactured by SLM to personalized lingual orthodontic brackets and surgical guide plates, the application of CoCrMo manufactured by SLM to knee prostheses and dental crowns and bridges, and the research results of Ti6Al4V manufactured by SLM in the treatment of pelvic fracture bone plates and personalized cranial prostheses. Finally, we introduce the development directions and research plans for SLM technology at the South China University of Technology, including the manufacture of a new porous structure by SLM directly, the manufacture by SLM of various material products simultaneously, SLM + material-reducing hybrid manufacturing, improving the negative feedback systems of SLM equipment, and developing SLM manufacturing processes using ceramics and new metals.

Key words: Selective laser melting (SLM); Biomedical metallic materials; Process parameters; Microstructure; Mechanical properties; Applications
https://doi.org/10.1631/jzus.A1700482 **CLC number:** TH122; TH162; TG456.7

1 Introduction

Selective laser melting (SLM) is a research hot spot in the field of additive manufacturing nowadays. It can be used directly to manufacture metal parts with metallurgical bonding, a compact structure, high dimensional accuracy, and good mechanical properties (Yang et al., 2013; Yap et al., 2015; Chua et al., 2017). The basic principle of the process is to slice the 3D parts, generate a trajectory for the laser beam in the section profile using path planning software, and import the obtained scanning trajectory data into the SLM manufacturing equipment. Then, a computer is used to control the laser beam to melt each layer of metal powder according to the scanning path and gradually add layer upon layer to obtain 3D solid metal parts (Kruth et al., 2005; Bremen et al., 2012; Yuan et al., 2017).

During the development of SLM over more than twenty years, several mature SLM equipment manufacturers have emerged around the world, including

---

‡ Corresponding author

* Project supported by the National Natural Science Foundation of China (No. 51405160), the Guangzhou Pearl River New Talent Project (No. 201710010064), the High-level Personnel Special Support Plan from Guangdong Province (No. 2016TQ03X289), the Instrument Research Project of the National Natural Science Foundation of China (No. 81327001), and the Application-oriented R&D Projects of Guangdong Province (No. 2015B090920002), China

ORCID: Yu-chao BAI, https://orcid.org/0000-0002-8517-6026

the EOS Company, Realizer Company, SLM Solutions Company, and Concept Laser Company in Germany, as well as the Renishaw Company in the UK (Hu et al., 2001). Although domestic research on SLM technology in China started late, a lot of effort has been put into research on the basic processes and equipment of SLM technology, and many excellent results have been obtained. The materials and processes of SLM technology have been studied for many years in Nanjing University of Aeronautics & Astronautics, China, including the cellular porous structure of 316L stainless steel manufactured by SLM, TiC_x/Ti nano-composite material, and the process, microstructure, and mechanical properties of nickel-based high temperature alloys manufactured by SLM (Gu et al., 2012a, 2012b; Jia and Gu, 2014; Dai and Gu, 2016). Selective laser sintering technology has been studied intensively by Huazhong University of Science and Technology, China. Based on this knowledge, the temperature field simulation and process optimization of SLM manufacturing were being studied by the beginning of 2003. The processing and properties of 316L die steel and stainless steel powder manufactured by SLM were also studied in depth (Yao et al., 2007; Liu B et al., 2009; Liu JH et al., 2010; Wei et al., 2011). The SLM direct-manufacture of aluminum alloy parts and SLM manufacturing with metal powder were studied at Beijing University of Technology, China (Zhang, 2007a, 2007b). Detailed research on laser net manufacturing technology was carried out by Northwestern Polytechnical University, China, and a deep exploration of SLM has recently begun (Cao et al., 2013; Huang et al., 2016). The microstructure and tensile properties of Ti6Al4V alloy manufactured by SLM were studied by the Beijing Aerospace Manufacturing Engineering Research Institute of Aviation Industry of China (Wu and Yang, 2007). Research on SLM technology at the South China University of Technology (SCUT) began in 2002. In 2004, the first set of selective laser melting equipment, DiMetal-240, was developed. Large scale equipment, DiMetal-280, was developed in 2007, and high precision equipment, DiMetal-100P, in 2012. So far, DiMetal-280, DiMetal-100, and DiMetal-50 have been developed and commercialized (Su and Yang, 2012; Wang et al., 2012, 2013; Yang, 2012; Sun et al., 2013; Liu et al., 2016).

Current research on SLM technology is focused mainly on the improvement of equipment performance, the development of new material technology, and many other applications. This paper introduces the progress made in research on SLM equipment, SLM manufacturing, and the application direction of biomedical metallic materials at SCUT, and introduces a new direction taken by SCUT in the field of SLM technology.

2 Research and development of SLM equipment in DiMetal series

SCUT has more than 10 years experience in the development of SLM series equipment. The key technologies were optimization of the laying of flexible powder, a method for overall sealing of the manufacturing room, and purification of circulating dust. Among the outputs, DiMetal-50 was a miniature SLM device in the DiMetal series developed specifically for dental and precious metal manufacturing, in which the powder cylinder and manufacturing cylinder were produced by a cylinder block with a diameter of 50 mm. This equipment greatly reduced the single-time use of materials and saved manufacturing costs, and so was particularly suitable for the rapid manufacture of small batch, personalized, and customized dental products and precious metal jewelry. Compared with other machines, the performance of the DiMetal series is excellent. The SLM manufacturing equipment of the DiMetal series is shown in Fig. 1.

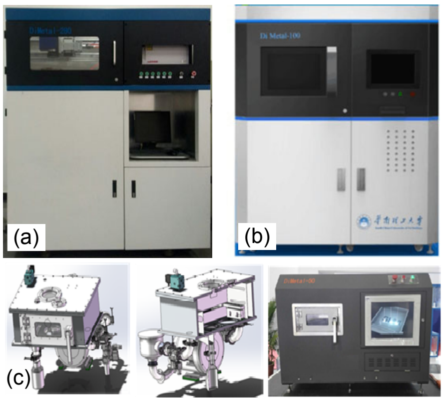

Fig. 1 DiMetal series equipment
(a) DiMetal-280; (b) DiMetal-100; (c) DiMetal-50

The main performance parameters of the equipment are shown in Table 1.

3 Research on the processing and properties of metal medical materials manufactured by SLM

3.1 Material composition and properties

There are three main kinds of SLM printing biomedical metallic materials: 316L stainless steel, CoCr alloy, and titanium alloy. The three kinds of powder all have spherical particle morphology (Fig. 2).

The 316L stainless steel metal powder prepared by the aerosol method is produced by the British company Sandvik Osprey. The particle size distribution is from 15 μm to 45 μm. The D10, D50, and D80 tested using a laser particle size analyzer are 22.5 μm, 39.02 μm, and 56.04 μm, respectively. The composition of the powder meets the requirements of ASTM F138-13a (ASTM, 2013b). CoCrMo alloy metal powder prepared by the aerosol method is produced by the British company Sandvik Osprey. Ninety percent of the particles are less than 22 μm. The average particle size (D50) of the powder is less than 28.5 μm, and the composition meets the requirements of ASTM F75-12 (ASTM, 2012). Ti6Al4V alloy powder prepared by the aerosol method is produced by the Wuxi Falcon Tech Company, China, and has a particle size concentrated in the range of 10–45 μm. The D50, as tested by a laser particle size analyzer, is 28.36 μm, and the composition of the powder meets the requirements of ASTM F136-13 (ASTM, 2013a). The specific components of the powders are shown in Table 2.

3.2 Optimization of process parameters

There are many parameters that affect SLM manufacturing, including laser parameters (laser

Table 1 Main parameters of DiMetal series equipment

Parameter	DiMetal-50	DiMetal-100	DiMetal-280
Laser type	Fiber laser		
Laser power	50 W, 100 W	200 W, 500 W	500 W
Manufacturing materials	Stainless steel, titanium alloy, aluminum alloy, tool steel, die steel, CoCr alloy, etc.		
Manufacturing size (long×width×height)	50 mm×50 mm×50 mm	100 mm×100 mm×120 mm	250 mm×250 mm×300 mm
Powder laying method	Double-cylinder unidirectional horizontal laying powder		Double-cylinder unidirectional and horizontal laying powder/ Single-cylinder feeding powder
Powder laying thickness	5–100 μm	5–100 μm	5–100 μm
Focal spot diameter	50–80 μm	80–100 μm	80–200 μm
Scanning speed of galvanometer	≥5 m/s	≥7 m/s	≥7 m/s
Manufacturing speed	2–15 cm^3/h	4–20 cm^3/h	6–30 cm^3/h
Manufacturing atmosphere	Vacuum, circulating purification, dust removal rate>95%		
Oxygen content in manufacturing chamber	0.12 mg/L	0.12 mg/L	0.12 mg/L
Manufacturing precision	0.1 mm	0.15 mm	0.15 mm
Density of manufacturing parts	Nearly 100%		
Surface roughness	RA 8–15 μm		
File format	STL and other convertible formats		
Supporting software	RP path scan (path scanning software) and RP control (system control software)		

RA means arithmetical mean deviation of the profile; STL means stereo lithography; RP means rapid prototyping

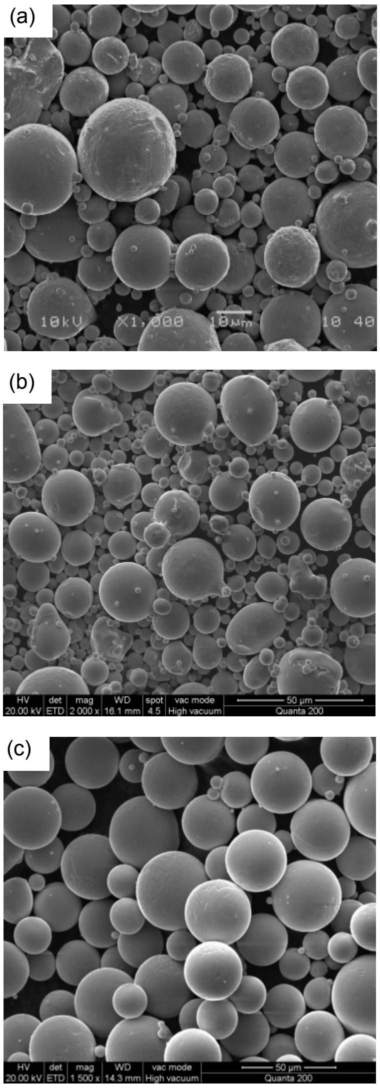

Fig. 2 Scanning electron microscope (SEM) morphology of powder of biomedical metallic materials
(a) 316L stainless steel; (b) CoCrMo alloy; (c) Ti6Al4V alloy

power, beam quality, spot diameter), mechanical motion parameters (powder laying speed, powder layer thickness), scanning parameters (scanning speed, spacing, strategy), and powder characteristics (powder component, particle size, morphology). This research is based on the DiMetal series SLM manufacturing equipment of SCUT, so the manufacturing process, equipment, and powder parameters of biomedical metallic materials of 316L stainless steel, CoCrMo alloy, and Ti6Al4V alloy are known. Therefore, the impacts of mainly laser power, scanning speed, scanning space, powder layer thickness, spot diameter, and scanning strategy on biomedical metallic powder manufacturing were studied. Through experimentation, the optimal process parameters were obtained (Table 3). Fig. 3 shows a schematic of the S-cross laying scanning strategy.

The SLM process parameters have a significant impact on the density, microstructure, and mechanical properties of the built parts. The density increases

Table 2 Composition of biomedical metallic powder

316L		CoCrMo		Ti6Al4V	
Element	Component	Element	Component	Element	Component
Fe	Balance	Co	Balance	Ti	Balance
Ni	12.06%	Cr	29.40%	Al	6.040%
Cr	17.53%	Mo	6.00%	V	3.940%
Mo	2.16%	Si	0.80%	Fe	0.020%
Si	0.86%	Mn	0.75%	Si	0.012%
C	0.03%	Fe	0.26%	C	0.013%
Mn	0.38%	N	0.19%	O	0.108%
P	0.02%	C	0.15%	N	0.013%
S	0.01%	Ni	0.09%	H	0.001%

Table 3 SLM manufacturing process parameters of biomedical metallic powders

Type	Laser power (W)	Scanning speed (mm/s)	Scanning space (μm)	Powder layer thickness (μm)	Spot diameter (μm)	Scanning strategy
316L stainless steel	160	450	80	25	80	S-cross laying
CoCrMo alloy	170	500	60	30	80	S-cross laying
Ti6Al4V alloy	150	600	80	30	80	S-cross laying

Note: The above optimal process parameters were obtained with a DiMetal-100 device, so they may not be completely applicable to other SLM devices. Different SLM equipment differs in its laser transmittance, manufacturing chamber environment, and evenness of powder laying, which results in changes of manufacturing parameters. With DiMetal series manufacturing equipment, the same kind of metal material has an optimized manufacturing parameter range, so the quality of manufacturing is the same in this section with increasing laser power. The reason is that high laser power leads to high energy input which can melt the metal powders sufficiently to enable dense metal parts to be obtained. But high scanning speed and scanning space will lead to a reduction of density due to the low energy input. The martensitic lath size in Ti6Al4V alloys is strongly influenced by the laser energy input, too. It increases with the energy input, which can be explained by the low cooling rate caused by the high energy input (Do and Li, 2016). Laser power influences elongation to failure, but has negligible effects on yield strength (YS) and ultimate tensile strength (UTS). The scanning space does not induce significant effects between 0.05 mm and 0.07 mm (Liverani et al., 2017).

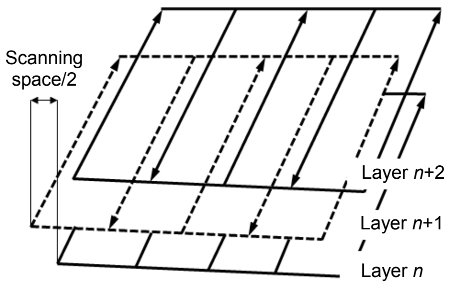

Fig. 3 A schematic of the S-cross laying scanning strategy

3.3 Microstructure

SLM direct manufacturing metal parts undergo rapid melting and cooling, with cooling speeds of up to 1×10^3 °C/s. Because of raid cooling, the crystal nucleation rate is greatly increased and grain size is suppressed at the same time. Therefore, microcellular crystals and columnar crystals of 1–10 μm are the main ingredients of the microstructure. The microstructure of 316L stainless steel, CoCrMo alloy, and Ti6Al4V manufactured by SLM has been studied by some researchers. Fig. 4a shows the microstructure of 316L stainless steel, in which the typical cellular grain microstructures can be seen clearly. The same results were also achieved by Sun et al. (2016). The microstructure of CoCrMo alloy (Fig. 4b) is nearly the same as that of 316L stainless steel. Hedberg et al. (2014) also found a cellular microstructure in his investigation on extracorporeal biocompatibility of CoCrMo dental alloys. Rafi et al. (2013) investigated the microstructure of Ti6Al4V, and observed the morphology of lath martensite from the SEM image shown in Fig. 4c.

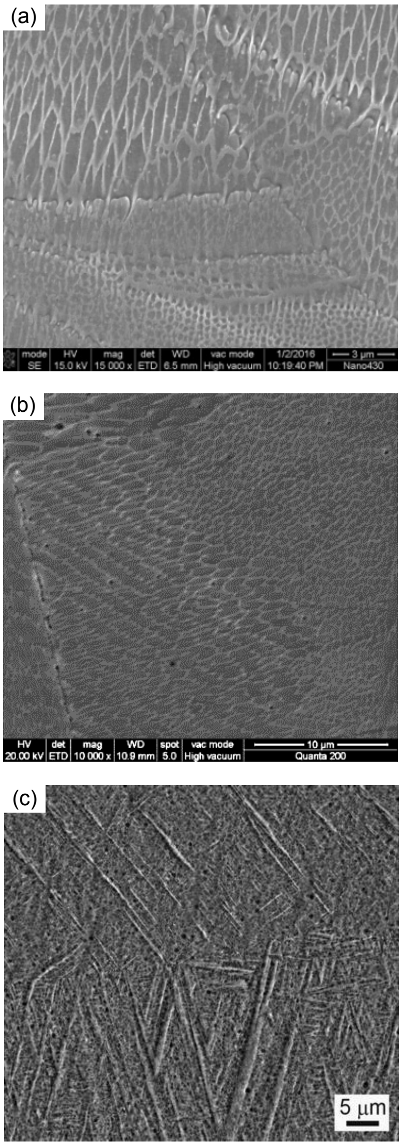

Fig. 4 Microstructure characteristics of biomedical metallic materials: (a) 316L stainless steel; (b) CoCrMo alloy; (c) Ti6Al4V alloy (Sun et al., 2016)

3.4 Properties of manufacturing parts

The SLM process of 316L stainless steel powder is quite mature. Compared to casting and ASTM A167-99(2009) (ASTM, 2009), the tensile strength, yield strength, and hardness of the powder have been significantly improved. The performance of CoCrMo alloy manufactured by SLM was tested under optimized process parameters. It was found that the performance of parts manufactured by SLM was related to the SLM manufacturing direction, and the tensile property of the parallel stacking layer was lower than that of the vertical stacking layer due to the constraint of the layer stacking manufacturing principle. Compared with the ASTM F75 standard, the tensile strength, yield strength, and Rockwell hardness of CoCr alloy manufactured by SLM are higher than those of the medical standards. The elongation is lower, but still in the range of the medical standard. Therefore, the CoCrMo alloy parts manufactured by SLM can be used in the rapid manufacture of personalized medical products. Titanium alloy has excellent corrosion resistance, good biocompatibility, low density, high specific strength, and other advantages. However, Young's modulus of titanium and titanium alloy does not match with that of natural bone. The difference in the mechanical properties of titanium and titanium alloy cannot be transferred well to the adjacent bone tissue by the implant, thus resulting in the stress shielding phenomenon. The mechanical properties of parts manufactured by SLM composed of the three kinds of materials are shown in Table 4. The performance of the parts produced by DiMetal series is as good as that of those produced by other machines (Sing et al., 2016; Fatemi et al., 2017).

4 Research on applications of SLM manufacturing to biomedical metallic materials

4.1 Research on applications of SLM manufacturing using 316L stainless steel

4.1.1 Personalized brackets

The technology of SLM direct manufacturing of 316L stainless steel invisible orthodontic brackets, dental implant guide plates, and surgical guide plates is widely used in medical treatment. Applying SLM manufacturing equipment DiMetal-280 and 316L stainless steel spherical powder with a size of 500 mesh, the key point of the SLM manufacturing of brackets is to ensure the manufacturing accuracy of the groove at 5 μm. Therefore, it is necessary to ensure not only an accurate laser energy input, but also a reasonable display space of the bracket in Magics software to enable the groove to be manufactured without an overhanging surface, adding extra metal supports and surface powder particle adhesion. Fig. 5 shows a diagram of the design of a personalized bracket, data processing in Magics software, SLM manufacturing of the bracket, and its post-processing.

4.1.2 An application of SLM manufacturing using 316L stainless steel: surgical guides

To overcome problems associated with the complexity of operations, poor accuracy, huge

Table 4 A comparison of the properties of metal parts (316L stainless steel, CoCrMo, and Ti6Al4V) manufactured by SLM with ASTM and the casting standard (Chlebus et al., 2011; Wang, 2011; Takaichi et al., 2013)

Material category		Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Elastic modulus (GPa)	Rockwell hardness (HRC)
316L stainless steel	ASTM F138-13a	190	490	40	210	22.2
	Casting	≥175	≥480	40	195	19
	SLM manufacturing	480	600	30	200	23
CoCrMo alloy	ASTM F75-12	450	655	>8	240	25
	Casting	620	845	10	220	33
	SLM manufacturing	689	970	3.1	230	40
	SLM with heat treatment	568	815	10.2	220	37
Ti6Al4V	ASTM F136-13	860	795	10	110	–
	Casting	976	847	5.1	114	–
	SLM manufacturing	1125	1250	6	94	41
	SLM with heat treatment	950	1005	12	115	37

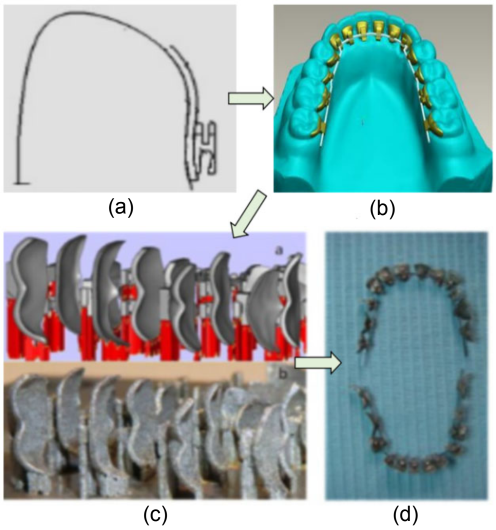

Fig. 5 Personalized design and SLM manufacturing of lingual orthodontic brackets
(a) Personalized backplane design; (b) Personalized tapping groove design; (c) Support added and SLM manufacturing; (d) Production

individual patient differences, and other issues of traditional surgical procedures, the use of personalized surgical guides is very important. Personalized surgical guides are customized according to the specific features of individual patients to achieve good positioning and accurate resection of the diseased part. Taking a femoral tumor for example, to remove the tumor accurately, computed tomography (CT) data of the patient is first analyzed using Mimics 10.0 software. Then, according to the threshold difference between the osteoma and normal bone, threshold segmentation is used to identify the tumor area in a reconstructed 3D femur model (Fig. 6a). The 3D model is imported into Pro/Engineer in STL format to construct the curved surface of the surgical guide, offsetting, merging, and substantiating according to the scope of surgical resection and fixation methods. On the basis of this, guide tubes, fixed holes, and other features can be added (Fig. 6b). Finally, a metal bone-cutting plate is manufactured that closely matches the lesion of the patient by using the SLM manufacturing equipment DiMetal-280. The material used is 316L stainless steel powder of 500 mesh. Simulated assembly is practised before the clinical application to ensure the correct bone-cutting effect. The preoperative simulation and intra-operative use of a personalized guide are shown in Figs. 6c and 6d.

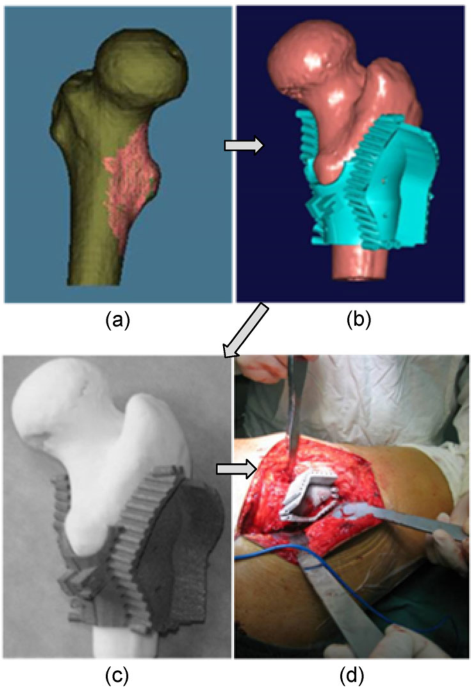

Fig. 6 Design, manufacturing, and application of a personalized surgical guide
(a) 3D reconstruction of CT; (b) Personalized design; (c) Try wearing after SLM; (d) Clinical application

4.2 Research on applications of SLM manufacturing using CoCrMo alloy

4.2.1 Knee prostheses

Since the size and shape of patients' knees are not the same, knee prostheses manufactured by traditional methods may result in poor individual fit and incomplete or excessive coverage of the intra-operative prosthesis and distal femoral bone-cutting face, leading eventually to increased risk of wear and loosening of the prosthesis. The best way to solve the problem of poor individual adaptation is to develop individualized treatment programs for patients and provide individualized adaptive prostheses. In the personalized femoral design scheme, a patient's CT data is first processed using Mimics 10.0 software, and then a 3D model of the knee is obtained according to the bone threshold covering membrane, region growth, and 3D calculation (Fig. 7a). The 3D model is output in STL format. The distal femoral surface is presented by Geomagic Studio software and substantiated as shown in Fig. 7b. The personalized femoral prostheses are designed according to the extracted individualized curved surface, the key anatomical data of patients, and conventional fixation features (Figs. 7 c and 7d). The adapted equipment is the SLM manufacturing equipment DiMetal-100, and the material is CoCrMo powder of 500 mesh. The individualized knee prostheses after direct manufacturing and polishing are shown in Figs. 7e and 7f, respectively.

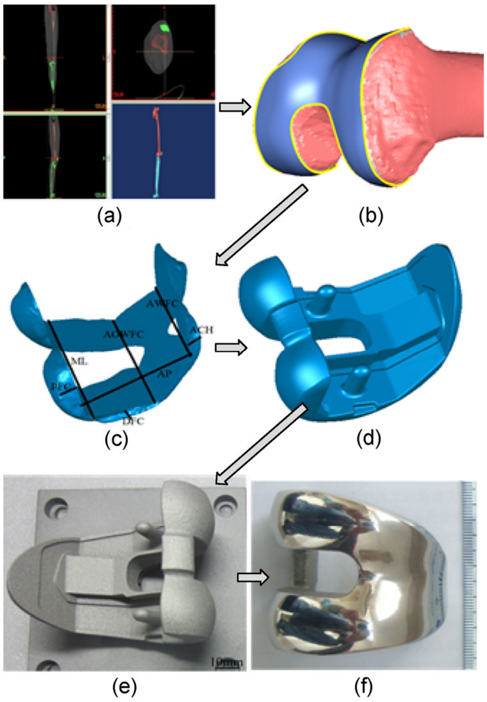

Fig. 7 Design of personalized total knee replacing femoral prostheses

(a) 3D reconstruction of CT data; (b) Surface extraction; (c) Section data measurement; (d) Individualized femoral prosthesis design; (e) SLM direct manufacturing; (f) Surface polishing

4.2.2 An application of SLM manufacturing using CoCr alloy: dental crowns and bridges

The SLM manufacturing procedure for dental crowns and bridges is the same as that used for general parts. It is necessary to consider that dental crowns and bridges are all small, thin-walled complex parts with curved surfaces. To ensure the effectiveness of repair, high manufacturing precision and surface quality of the dental crown and bridge are required. Thus, the laser energy input of the manufacturing process should be controlled well. The model of the teeth is divided after scanning and the dental crown and bridge are designed using dedicated dental software (Fig. 8). The design data is imported into Magic software to add the support and slice. The SLM manufacturing equipment DiMetal-100 is then used to manufacture the CoCr alloy dental crown and bridge, which needs support removal, surface polishing, follow-up porcelain, and other processes after manufacture. SLM manufactured parts used for restoration have a dense interior and high accuracy. A long bridge can also be produced at one time without follow-up welding. Scanning of the SLM dental crown and bridge with a Vtop 200B 3D scanner showed that the error was very small (Mai, 2015).

4.3 Applications of SLM manufacturing using Ti6Al4V

4.3.1 Pelvic fracture bone plates

An individualized bone plate was designed based on the analysis of a pelvic fracture of a patient. To improve the quality of fracture reduction and reduce the operation time, SLM direct-rapid manufacturing was adopted to fabricate a Ti6Al4V personalized bone plate. The key technical steps of the process were as follows: the design of the individualized bone plate based on the doctor's clinical experience, 3D metal printing and quality control of the plate, vacuum heat treatment, preoperative simulation exercise, clinical application, and evaluation. As for the quality control of SLM processing of a personalized bone plate, the fitting surface of the plate was put upwards to ensure the machining accuracy and complex surface fitting effect of the plate, thereby improving its surface quality and the pelvic junction surface. The residual stress of the titanium alloy plate manufactured by SLM was removed by vacuum heat treatment. The hardness of the plate was HV1360–HV1390, the tensile strength 1000–1100 MPa, the

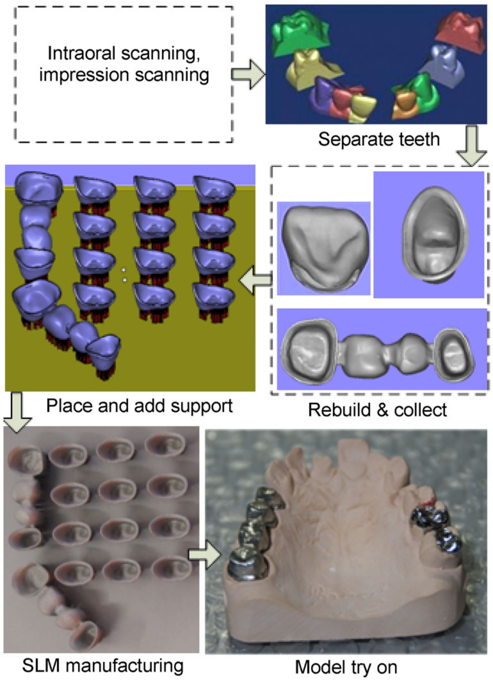

Fig. 8 SLM manufacturing of the individualized dental crown and bridge

yield strength 900–950 MPa, and the elongation rate 8%–10%. The mechanical performance requirements of a medical bone plate were satisfied. A preoperative matching experiment and surgical drilling were performed on the surface-treated bone plate and the pelvic model of acrylonitrile butadiene styrene (ABS) material. Finally, the personalized bone plate was applied in the clinical operation. The intra-operative C-arm and post-operative CT images showed that the personalized bone plate and broken pelvis matched perfectly, which not only enabled the fixing of bone fragments but also aided pelvic recovery. The operation time was reduced to about 2 h. A personalized bone plate manufactured by combining digital design and metal 3D printing methods has the following advantages: a perfect fit to the fracture block of the patient, no preoperative bending of the titanium plate, and a sharp reduction in surgical wounding and operation time, thereby enabling minimal invasive treatment of pelvic and acetabular fractures. The whole processes of digital design, SLM manufacturing, polishing and other post-processing, and clinical application of the Ti6Al4V personalized bone plate are shown in Fig. 9.

4.3.2 Personalized skull restoration

For the design and SLM manufacturing of personalized skull restoration parts, the CT data of patients is first put into Mimics software, then a 3D reconstruction of the skull defect site is performed using a left and right mirror method to obtain a matching shape. The 3D model of the reconstructed defect site is divided into hexahedral meshes. The size of the unit body is set. A model of the porous skull restoration is then constructed. Considering the high stiffness of metallic skull restoration, which contributes to the stress shielding phenomenon, topology optimization is used to reduce negative effects (Al-Tamimi et al., 2017). Finally, the skull restoration part is obtained by SLM processing with the SLM manufacturing equipment Metal-100 and Ti6Al4V of 500 mesh, which can be used clinically after sandblasting, ultrasonic cleaning, and high temperature sterilization. The whole process is shown in Fig. 10.

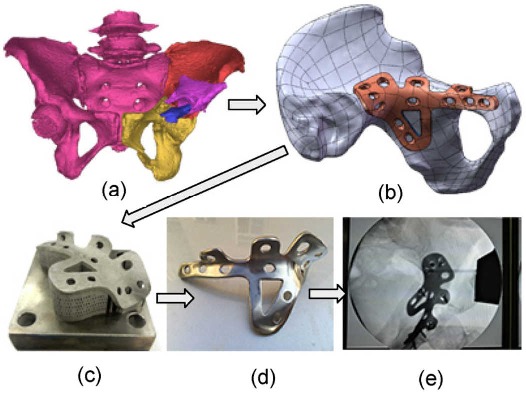

Fig. 9 Design and SLM manufacturing processes of a Ti6Al4V personalized bone plate

(a) 3D reconstruction of CT data; (b) Design; (c) SLM manufacturing; (d) Post-processing; (e) Implant

5 Future research plans

5.1 Porous structure

At present, the methods used to design porous structures are mainly constructive solid geometry methods based on UG, CATIA, and other computer aided design (CAD) software, and design methods based on Micro-CT, CT, and other images. Although these methods are widely used, they cannot effectively control and estimate the structural and mechanical properties, and have the disadvantages of a complicated realization process, large data volume, and low computational efficiency. At SCUT, the basic porous unit has been mapped to each grid cell structure by dividing the implant into the grid cell structure and establishing node information (Xiao, 2013). The unit porous structure contour node is transformed in the Cartesian coordinate system according to the partitioned mesh node information to obtain the same subunit as the meshing unit. All the subunits are reunited in the spatial domain to obtain a connected porous implant model. This method (Fig. 11) not only significantly reduces the weight of the implant, but also facilitates the intermeshing fixation of the implant with the host bone and provides good biomechanical properties.

5.2 Multi-material manufacturing

Due to the limitations of the structure of the SLM equipment, early SLM manufacturing involved mainly the manufacture of a single material at a time, which severely limited its application. Researchers have carried out a preliminary study on the powder feeding methods of multi-materials and the binding properties of different materials (Fig. 12). The key technical questions are how to ensure that a variety of powder materials can be accurately preset to a specified location, avoiding powder mixing caused by switching, and how to ensure the metallurgical bonding properties between different powders. Some studies have investigated processing of multiple materials such as AlSi10Mg-C18400 and 316L-C18400 copper alloys (Liu et al., 2014; Sing et al., 2015). However, at present, research progress on multi-materials manufactured by SLM is still confined to simple box manufacturing, and it is not possible to manufacture complex or arbitrary distributed products (Badrossamay and Childs, 2007).

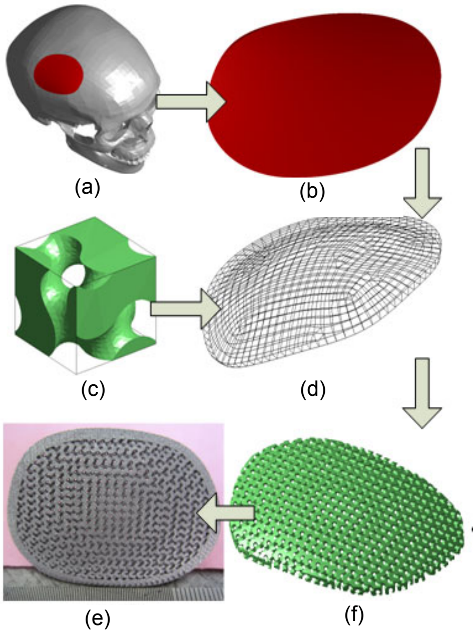

Fig. 10 Design and SLM manufacturing of a porous skull restoration

(a) CT skull reconstruction; (b) Skull repair appearance; (c) Basic unit structure; (d) Unit division; (e) SLM manufacturing; (f) Unit mapping

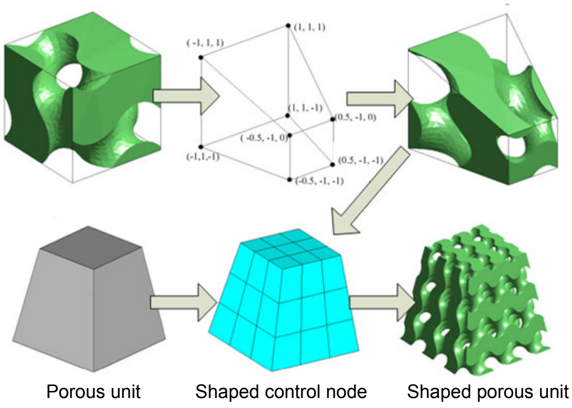

Fig. 11 Obtaining a porous implant by the mapping of a shaped control node

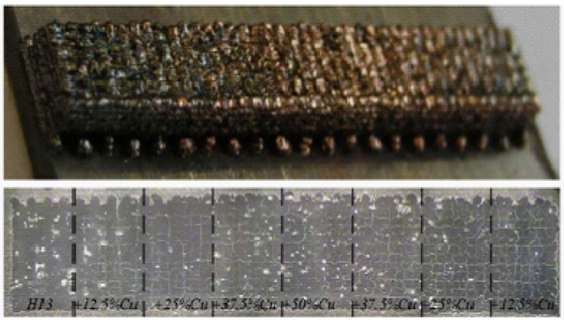

Fig. 12 SLM manufacturing using multi-component materials

5.3 Hybrid manufacturing

The principle of SLM technology is to manufacture layer by layer. Although SLM direct-manufactured parts have the characteristics of a high degree of freedom and rapid correspondence, the parts have a rough surface of relatively poor quality, and are unable to meet the high precision requirements of special parts owing to the spheroidizing effect of metal material and the existence of curved surfaces on most parts. The cutting process of conventional machining is able to produce parts with high surface accuracy. Therefore, researchers have tried to combine SLM manufacturing process with cutting process to form hybrid processing equipment and have obtained excellent results. In hybrid process manufacturing, parts with a certain height are first obtained by SLM manufacturing. Then, the surface of the formed parts is milled with a milling cutter, and the two processes cycle continuously. Finally, functional parts with complex spatial structures and good surface quality are obtained. A complicated mold manufactured by a hybrid manufacturing machine combining SLM and the cutting process has been developed by the Japanese Matsuura Machinery Corporation (Fig. 13) (Leng, 2015). The surface of the mold has a metallic luster and good quality.

Fig. 13 A hybrid manufacturing process mold developed by the Japanese Matsuura Machinery Corporation

5.4 Negative feedback system of SLM equipment

SLM manufacturing is a complex solid-liquid-gas interaction process, in which a laser and inert shielding gas have a great impact on the manufacturing quality. Due to vibration, airflow, thermal change, and other unstable factors in the manufacturing process, the laser beam energy accepted by metal powder in the manufacturing process fluctuates sharply. Therefore, it is necessary to monitor heat in the weld pool and send a feedback signal to the laser control system to realize dynamic monitoring and adjustment of the laser energy.

Because of the nature of the powder itself, equipment restrictions, and other factors, a certain amount of oxygen or oxide will be introduced. The oxide particles produced will float in the manufacturing chamber or fall into the powder bed and onto the surface of manufactured parts in the manufacturing process. In addition, the movement of the powder laying device and excessive protective gas flow will also cause a small amount of powder to rise, which may damage the laser lens and laser beam. Therefore, it is necessary to add an air pressure sensor, oxygen content detector, and dust detector in the manufacturing chamber to monitor the air environment. The signal obtained will be fed back to the gas circulation cleaning device and the shielding gas control device. By adjusting the protective gas flow and the strength of the purifying device, the oxygen and floating solid particles can be removed from the manufacturing chamber to maintain the normal manufacturing environment.

Domestic and foreign research institutions are beginning to study the monitoring of the SLM manufacturing process for sparks and other physical signals in the molten pool. They take pictures of each layer of SLM manufacturing to reveal the construction process of 3D entities.

5.5 SLM manufacturing using ceramics and new metals, and other research directions

Ceramic material has the advantages of heat resistance, high strength, and high wear resistance, which other metal materials lack. However, it has a high melting point and low plasticity, and is prone to crack during high speed cooling. A study of the ZrO_2-Al_2O_3 ceramic SLM manufacturing process found that a 1700 °C preheating temperature can reduce the cracking in SLM ceramic manufacturing to obtain parts with better quality (Wilkes et al., 2013). Commercial SLM equipment with a high-energy-density laser beam has also been used to obtain large-scale complex ceramic parts with a density of more than 90% (Juste et al., 2014). Some other researchers have studied the processing and properties of ceramics in selective laser melting and sintering (Gan and Wong, 2017; Sing et al., 2017).

Magnesium has been considered among a new generation of implant materials which are bioactive, biodegradable, and suitable for orthopaedic applications. Savalani and Pizarro (2016) investigated the effects of preheating and layer thickness on SLM of magnesium using a pulse mode. They showed that a successful processing window can be identified if the magnesium powder is preheated prior to processing, and that both the preheating and layer thickness parameters have an effect on the dimensional and mechanical properties of the tracks fabricated (Savalani and Pizarro, 2016). Yang et al. (2016) studied the effects of process parameters on the formability quality and properties of SLM-processed magnesium parts. They found that dense magnesium parts without pores or cracks could be obtained with an optimal laser energy density of 10.0 J/mm (Yang et al., 2016). Using additive manufacturing to fabricate smart materials and structures, also called "4D printing", has attracted increasing attention (Khoo et al., 2015). Li et al. (2016) studied the development of TiNi-based negative Poisson's ratio structures using additive manufacture (AM).

The other research directions of SLM include the manufacture of large-size and complex pieces (a unidirectional size of x or y of at least more than 500 mm), large-scale manufacturing with less accumulation of internal stress, and multi-laser high-efficiency manufacturing. With more research on applications, the combination of SLM and traditional manufacturing technologies will gradually become a bright spot in the advanced manufacturing industry.

6 Summary

The South China University of Technology has conducted a detailed long-term study of SLM equipment and its applications in medicine, studied the SLM manufacturing process and the microstructure of biomedical metal materials of 316L stainless steel, CoCrMo alloy, and Ti6Al4V alloy, and obtained parts with outstanding performance. The 316L stainless steel manufactured by SLM has been successfully applied to orthodontic brackets and surgical guides. The CoCrMo alloy manufactured by SLM has been applied to knee prostheses and dental crowns and bridges. The Ti6Al4V alloy manufactured by SLM has been applied to individualized bone plates and skull porous prostheses. Among these, the orthodontic brackets and dental crowns and bridges have become commercial applications.

At present, researchers at SCUT are beginning to study the design and manufacturing technology needed for the internal structure of implants. At the same time, research on SLM multi-material manufacturing and SLM + material-reducing hybrid manufacturing has been started, and SCUT has begun the development of an SLM equipment negative feedback system and research on the ceramic SLM manufacturing process.

References

Al-Tamimi AA, Fernandes PRA, Peach C, et al., 2017. Metallic bone fixation implants: a novel design approach for reducing the stress shielding phenomenon. *Virtual and Physical Prototyping*, 12(2):141-151. https://doi.org/10.1080/17452759.2017.1307769

ASTM (American Society for Testing and Materials), 2009. Standard Specification for Stainless and Heat-resisting Chromium-Nickel Steel Plate, Sheet, and Strip, ASTM A167-99(2009). ASTM International, West Conshohocken, USA.

ASTM (American Society for Testing and Materials), 2012. Standard Specification for Cobalt-28 Chromium-6 Molybdenum Alloy Castings and Casting Alloy for Surgical Implants (UNS R30075), ASTM F75-12. ASTM International, West Conshohocken, USA.

ASTM (American Society for Testing and Materials), 2013a. Standard Specification for Wrought Titanium-6Aluminum-4Vanadium ELI (Extra Low Interstitial) Alloy for Surgical Implant Applications (UNS R56401), ASTM F136-13. ASTM International, West Conshohocken, USA.

ASTM (American Society for Testing and Materials), 2013b. Standard Specification for Wrought 18Chromium-14Nickel-2.5Molybdenum Stainless Steel Bar and Wire for Surgical Implants (UNS S31673), ASTM F138-13a. ASTM International, West Conshohocken, USA.

Badrossamay M, Childs THC, 2007. Further studies in selective laser melting of stainless and tool steel powders.

International Journal of Machine Tools & Manufacture, 47(5):779-784.
https://doi.org/10.1016/j.ijmachtools.2006.09.013

Bremen S, Meiners W, Diatlov A, 2012. Selective laser melting. *Laser Technik Journal*, 9(2):33-38.
https://doi.org/10.1002/latj.201290018

Cao J, Liu F, Lin X, et al., 2013. Effect of overlap rate on recrystallization behaviors of laser solid formed Inconel 718 superalloy. *Optics & Laser Technology*, 45:228-235.
https://doi.org/10.1016/j.optlastec.2012.06.043

Chlebus E, Kuznicka B, Kurzynowski T, et al., 2011. Microstructure and mechanical behaviour of Ti-6Al-7Nb alloy produced by selective laser melting. *Materials Characterization*, 62(5):488-495.
https://doi.org/10.1016/j.matchar.2011.03.006

Chua CK, Wong CH, Yeong WY, 2017. Standards, Quality Control and Measurement Sciences. 3D Printing and Additive Manufacturing. Academic Press, New York, USA, p.91-153.
https://doi.org/10.1142/10200

Dai DH, Gu DD, 2016. Tailored reinforcement/matrix interface and thermodynamic mechanism during selective laser melting composites. *Materials Science and Technology*, 32(7):617-628.
https://doi.org/10.1179/1743284715Y.0000000012

Do DK, Li P, 2016. The effect of laser energy input on the microstructure, physical and mechanical properties of Ti-6Al-4V alloys by selective laser melting. *Virtual and Physical Prototyping*, 11(1):41-47.
https://doi.org/10.1080/17452759.2016.1142215

Fatemi SA, Ashany JZ, Aghchai AJ, et al., 2017. Experimental investigation of process parameters on layer thickness and density in direct metal laser sintering: a response surface methodology approach. *Virtual and Physical Prototyping*, 12(2):133-140.
https://doi.org/10.1080/17452759.2017.1293274

Gan MX, Wong CH, 2017. Properties of selective laser melted spodumene glass-ceramic. *Journal of the European Ceramic Society*, 37(13):4147-4154.
https://doi.org/10.1016/j.jeurceramsoc.2017.04.060

Gu DD, Meiners W, Wissenbach K, et al., 2012a. Laser additive manufacturing of metallic components: materials, processes and mechanisms. *International Materials Reviews*, 57(3):133-164.
https://doi.org/10.1179/1743280411Y.0000000014

Gu DD, Meng GB, Li C, et al., 2012b. Selective laser melting of TiC/Ti bulk nanocomposites: influence of nanoscale reinforcement. *Scripta Materialia*, 67(2):185-188.
https://doi.org/10.1016/j.scriptamat.2012.04.013

Hedberg YS, Qian B, Shen Z, et al., 2014. In vitro biocompatibility of CoCrMo dental alloys fabricated by selective laser melting. *Dental Materials*, 30(5):525-534.
https://doi.org/10.1016/j.dental.2014.02.008

Hu XD, Zhao WH, Li DC, 2001. Review and prospect of directly metal forming technology. *Tool Engineering*, 35(10):3-6.

Huang C, Lin X, Liu F, et al., 2016. Effects of cooling condition on microstructure and mechanical properties in laser rapid forming of 34CrNiMo6 thin-wall component. *The International Journal of Advanced Manufacturing Technology*, 82(5-8):1269-1279.
https://doi.org/10.1007/s00170-015-7453-z

Jia QB, Gu DD, 2014. Selective laser melting additive manufacturing of Inconel 718 superalloy parts: densification, microstructure and properties. *Journal of Alloys and Compounds*, 585:713-721.
https://doi.org/10.1016/j.jallcom.2013.09.171

Juste E, Petit F, Lardot V, et al., 2014. Shaping of ceramic parts by selective laser melting of powder bed. *Journal of Materials Research*, 29(17):2086-2094.
https://doi.org/10.1557/jmr.2014.127

Khoo ZX, Teoh JEM, Liu Y, et al., 2015. 3D printing of smart materials: a review on recent progresses in 4D printing. *Virtual and Physical Prototyping*, 10(3):103-122.
https://doi.org/10.1080/17452759.2015.1097054

Kruth JP, Mercelis P, van Vaerenbergh J, et al., 2005. Binding mechanisms in selective laser sintering and selective laser melting. *Rapid Prototyping Journal*, 11(1):26-36.
https://doi.org/10.1108/13552540510573365

Leng Y, 2015. Additive Manufacturing + Reducing Cutting Compound Processing Technology.
http://www.chinabaike.com/t/9541/2016/0701/5522669.html

Li S, Hassanin H, Attallah MM, et al., 2016. The development of TiNi-based negative Poisson's ratio structure using selective laser melting. *Acta Materialia*, 105:75-83.
https://doi.org/10.1016/j.actamat.2015.12.017

Liu B, Zhang LC, Mo JH, et al., 2009. New method of improving parts accuracy by adding heat balance support in selective laser sintering. *Journal of Zhejiang University-SCIENCE A*, 10(3):361-369.
https://doi.org/10.1631/jzus.A0820226

Liu JH, Li RD, Zeng WX, et al., 2010. Study on formation of surface and microstructure of stainless steel part produced by selective laser melting. *Materials Science and Technology*, 26(10):1259-1264.
https://doi.org/10.1179/174328409X441300

Liu Q, Wang Y, Zheng H, et al., 2016. Microstructure and mechanical properties of LMD-SLM hybrid forming Ti6Al4V alloy. *Materials Science and Engineering: A*, 660:24-33.
https://doi.org/10.1016/j.msea.2016.02.069

Liu ZH, Zhang DQ, Sing SL, et al., 2014. Interfacial characterization of SLM parts in multi-material processing: metallurgical diffusion between 316L stainless steel and C18400 copper alloy. *Materials Characterization*, 94:116-125.
https://doi.org/10.1016/j.matchar.2014.05.001

Liverani E, Toschi S, Ceschini L, et al., 2017. Effect of selective laser melting (SLM) process parameters on microstructure and mechanical properties of 316L austenitic stainless steel. *Journal of Materials Processing Technology*, 249:255-263.

Mai SZ, 2015. Study on the Forming Processes and Properties of Customized CoCr Alloy Crowns and Fixed Bridges Manufactured by Selective Laser Melting. MS Thesis, South China University of Technology, Guangzhou, China (in Chinese).

Rafi HK, Karthik NV, Gong H, et al., 2013. Microstructures and mechanical properties of Ti6Al4V parts fabricated by selective laser melting and electron beam melting. *Journal of Materials Engineering and Performance*, 22(12): 3872-3883.
https://doi.org/10.1007/s11665-013-0658-0

Savalani MM, Pizarro JM, 2016. Effect of preheat and layer thickness on selective laser melting (SLM) of magnesium. *Rapid Prototyping Journal*, 22(1):115-122.
https://doi.org/10.1108/RPJ-07-2013-0076

Sing SL, Lam LP, Zhang DQ, et al., 2015. Interfacial characterization of SLM parts in multi-material processing: intermetallic phase formation between AlSi10Mg and C18400 copper alloy. *Materials Characterization*, 107: 220-227.
https://doi.org/10.1016/j.matchar.2015.07.007

Sing SL, An J, Yeong WY, et al., 2016. Laser and electron-beam powder-bed additive manufacturing of metallic implants: a review on processes, materials and designs. *Journal of Orthopaedic Research*, 34(3):369-385.
https://doi.org/10.1002/jor.23075

Sing SL, Yeong WY, Wiria FE, et al., 2017. Direct selective laser sintering and melting of ceramics: a review. *Rapid Prototyping Journal*, 23(3):611-623.
https://doi.org/10.1108/RPJ-11-2015-0178

Su X, Yang Y, 2012. Research on track overlapping during selective laser melting of powders. *Journal of Materials Processing Technology*, 212(10):2074-2079.
https://doi.org/10.1016/j.jmatprotec.2012.05.012

Sun J, Yang Y, Wang D, 2013. Mechanical properties of a Ti6Al4V porous structure produced by selective laser melting. *Materials & Design*, 49:545-552.
https://doi.org/10.1016/j.matdes.2013.01.038

Sun Z, Tan X, Tor SB, et al., 2016. Selective laser melting of stainless steel 316L with low porosity and high build rates. *Materials & Design*, 104:197-204.
https://doi.org/10.1016/j.matdes.2016.05.035

Takaichi A, Nakamoto T, Joko N, et al., 2013. Microstructures and mechanical properties of Co-29Cr-6Mo alloy fabricated by selective laser melting process for dental applications. *Journal of the Mechanical Behavior of Biomedical Materials*, 21(3):67-76.
https://doi.org/10.1016/j.jmbbm.2013.01.021

Wang D, 2011. Study on the Fabrication Properties and Process of Stainless Steel Parts by Selective Laser Melting. PhD Thesis, South China University of Technology, Guangzhou, China (in Chinese).

Wang D, Yang YQ, Su XB, et al., 2012. Study on energy input and its influences on single-track, multi-track, and multi-layer in SLM. *The International Journal of Advanced Manufacturing Technology*, 58(9-12):1189-1199.
https://doi.org/10.1007/s00170-011-3443-y

Wang D, Yang Y, Liu R, et al., 2013. Study on the designing rules and processability of porous structure based on selective laser melting (SLM). *Journal of Materials Processing Technology*, 213(10):1734-1742.
https://doi.org/10.1016/j.jmatprotec.2013.05.001

Wei QS, Zhao X, Wang L, et al., 2011. Effects of the processing parameters on the forming quality of stainless steel parts by selective laser melting. *Advanced Materials Research*, 189-193:3668-3671.
https://doi.org/10.4028/www.scientific.net/AMR.189-193.3668

Wilkes J, Hagedorn YC, Meiners W, et al., 2013. Additive manufacturing of ZrO_2-Al_2O_3 ceramic components by selective laser melting. *Rapid Prototyping Journal*, 19(1): 51-57.
https://doi.org/10.1108/13552541311292736

Wu WY, Yang YQ, 2007. Key techniques of selective laser melting rapid prototyping system. *Chinese Journal of Mechanical Engineering*, 43(08):175-180.
https://doi.org/10.3901/JME.2007.08.175

Xiao DM, 2013. Modeling of Porous Structure of Implants and Direct Manufacturing by Selective Laser Melting. PhD Thesis, South China University of Technology, Guangzhou, China (in Chinese).

Yang YQ, 2012. Accuracy and density optimization in directly fabricating customized orthodontic production by selective laser melting. *Rapid Prototyping Journal*, 18(6):482-489.
https://doi.org/10.1108/13552541211272027

Yang YQ, Liu Y, Song CH, 2013. The status and progress of manufacturing of metal parts by 3D printing technology. *Mechanical & Electrical Engineering Technology*, 42(4): 1-7.

Yang YW, Wu P, Lin X, et al., 2016. System development, formability quality and microstructure evolution of selective laser-melted magnesium. *Virtual and Physical Prototyping*, 11(3):173-181.
https://doi.org/10.1080/17452759.2016.1210522

Yao H, Shi Y, Zhang W, et al., 2007. Numerical simulation of the temperature field in selective laser. *Applied Laser*, 27(6):456-460.

Yap CY, Chua CK, Dong ZL, et al., 2015. Review of selective laser melting: materials and applications. *Applied Physics Reviews*, 2(4):041101.
https://doi.org/10.1063/1.4935926

Yuan B, Zhou SY, Chen XS, 2017. Rapid prototyping technology and its application in bone tissue engineering.

Journal of Zhejiang University-SCIENCE B (Biomedicine & Biotechnology), 18(4):303-315. https://doi.org/10.1631/jzus.B1600118

Zhang DY, 2007a. Effect of properties of powders on manufacturing process (SLM) of metallic models. *Applied Laser*, 27(1): 9-12.

Zhang DY, 2007b. Model manufacturing process from aluminum alloys using selective laser melting. *Chinese Journal of Lasers*, 34(12):1700-1704.

中文概要

题　目：激光选区熔化设备及生物医学金属材料的研究与应用进展

摘　要： 本文主要介绍了华南理工大学（SCUT）在激光选区熔化（SLM）成型设备以及医用金属材料SLM成型的基础研究与应用的最新成果。首先，采用DiMetal-100设备研究316L不锈钢、CoCrMo与Ti6Al4V三种医用金属粉末SLM成型的工艺参数、微观组织和力学性能。其次，详细介绍了SLM成型316L不锈钢在个性化舌侧正畸托槽和手术导板的应用，SLM成型CoCrMo在膝关节假体和牙冠牙桥的应用，以及SLM成型Ti6Al4V在骨盆骨折接骨板和个性化颅骨修复体方面的研究成果。最后，介绍了SCUT在SLM技术方面的发展方向和研究计划，具体包括实现新型多孔结构的SLM直接成型、实现多种材料SLM一次成型、实现SLM与减材复合成型、增加SLM设备的负反馈系统以及开发陶瓷和新型金属的SLM成型工艺。

总　结： SCUT对SLM设备及其医学应用进行了长期深入的研究，研究了医用金属材料316L不锈钢、CoCrMo合金以及Ti6Al4V合金的SLM成型工艺和微观组织，获得了性能优异的零件。SCUT成功将SLM成型的316L不锈钢应用于舌侧正畸托槽和手术导板，将SLM成型的CoCrMo合金应用于膝关节假体和牙冠牙桥，以及将SLM成型的Ti6Al4V合金应用于个性化接骨板和颅骨多孔修复体。其中，舌侧正畸托槽和牙冠固定桥已经进入商业应用。目前，SCUT正在进一步开展面向植入体内部结构的设计和制造技术研究，同时开始对SLM多材料成型、SLM与切削复合成型进行研究，并逐步开展SLM设备负反馈系统的开发及陶瓷、锌合金、镍钛合金等SLM成型工艺的研究等。

关键词： 激光选区熔化（SLM）；生物医学金属材料；工艺参数；微观组织；机械性能；应用