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LARGE-SCALE EQUIPMENT AND HIGHER PERFORMANCE MATERIALS FOR LASER ADDITIVE MANUFACTURING

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ABSTRACT: The current available selective laser sintering (SLS) and selective laser melting (SLM) equipment has a relatively small effective building volume, which does not offer capability to integrally manufacture a larger dimension component. Therefore, our research team has investigated key SLS processing techniques such as the large powder bed preheating system and multi-laser scanning system, and then successfully developed a series of large-scale SLS systems with the effective building volumes of $1400 \times 700 \times 500 \text{ mm}^3$ and $1400 \times 1400 \times 500 \text{ mm}^3$, and SLM system with the effective building volume of $500 \times 250 \times 400 \text{ mm}^3$. These large scale SLS/SLM systems will not only offer new capability to make large complex prototypes and products, but also provide higher volume production capability to make numerous small parts rapidly and cost-effectively. High performance materials have been developed for the large-scale SLS/SLM systems. Especially, nylon coated composite powders were prepared by a dissolution-precipitation process, which is able to uniformly disperse the micro/nano-scale filler particles in the nylon matrix, and thus enhance the properties of nylon SLS parts.

1 INTRODUCTION

Over the past few decades, great progress has been made on the development of new techniques and advanced materials for additive manufacturing (AM) technology. Selective laser sintering (SLS) and selective laser melting (SLM) are the two versatile laser-based additive manufacturing processes. SLS/SLM can directly manufacture three-dimensional components according to computer aided design (CAD) models by selectively sintering/melting successive layers of powdered materials using lasers (Kumar, 2003; Pham et al., 1999; Kruth et al., 2003). It has great potential to manufacture complex and low volume parts more rapidly and cost-effectively, as compared with conventional manufacturing methods.

However, the current available SLS equipment has a relatively small effective building platform with a dimension less than 1.0 m, and thus cannot build a large part with a size more than 1.0 m. EOS GmbH is the world leader in laser sintering additive manufacturing, and produces various kinds of laser sintering machines, among which EOSINT S 750 has the largest effective building volume of $720 \times 380 \times 380 \text{ mm}^3$ (EOSINT 750 Data Sheet). Therefore, it is impossible to make a large component with a dimension more than 720 mm. The largest SLM system of EOS is EOS M 400 with a building volume of $400 \times 400 \times 400 \text{ mm}^3$. The current method to address this problem is to cut the CAD model of the parts into several pieces, then manufacture the pieces separately and finally assemble them together to form a large dimension component. Obviously, this separate manufacture and assembling method influences part accuracy and require high cost and production time. Consequently, we have investigated key SLS processing techniques such as the large powder bed preheating system, multi-laser scanning system, data processing software, etc. and successfully developed a series of large-scale SLS equipment with effective building volumes of $1400 \times 700 \times 500 \text{ mm}^3$ and $1400 \times 1400 \times 500 \text{ mm}^3$, and SLM system with the effective building

volume of $500 \times 250 \times 400 \text{ mm}^3$. These large-scale SLS with high effective building volumes will not only offer new capability to make large complex prototypes and products, but also provide higher volume production capability to make numerous small parts rapidly and cost-effectively. In addition, high performance materials have been developed for the large-scale SLS/SLM systems.

2 LARGE-SCALE SLS EQUIPMENT AND HIGH PERFORMANCE MATERIALS

Nowadays, it is difficult for the current techniques to realize large-scale SLS equipment with a large effective building platform (the size more than 1000 mm). This is due to fact that some technical difficult problems such as uniform control of preheating temperature, multi-laser scanning and high performance materials are not solved.

2.1 Development of large-scale SLS equipment

2.1.1 Multi-layer adjustable preheating device and self-adaptive preheating method

Figure 1. (a) Multi-layer adjustable preheating device, and (b) temperature distribution in the whole platform.

In the SLS process, the part bed should be uniformly pre-heated to a temperature referred to as part bed temperature by the heating system (see Fig. 1) for the purpose of building parts with no distortion. However, when the platform of SLS machines is enlarged, the current single layer heating system is not able to realize a uniform temperature field in the whole platform, thus leading to part deformation. To address this problem, we develop a powder bed pre-heating system called multi-layer adjustable preheating device based on self-adaptive fuzzy control as shown in Fig.1 (a) and overcome the uniformity problem of the pre-heating temperature field of extended large powder bed. The simulation result in Fig.1 (b) reveals the uniform temperature distribution in the whole platform.

We use self-adaptive preheating methods, in which overhang layers can be identified automatically, and preheat temperature for these overhang layers will be increased to limit the occurrence of deformation or reduce the degree of deformation. When the preheating temperature exceeds the glass transition temperature of the polymer about 150°C , the powder outside the sintering zone melts and some agglomeration occurs. The agglomerated area acts as a restraint on the workpiece and can suppress deformation. In addition, increasing of preheating temperature

raises the surface temperature of the sintered layer, which reduces the inconsistency of the temperature, and also reduces the uneven shrinkage and non-uniform stress due to non-uniform temperature field, thus leading to improved precision of parts. The overhang layers are defined as a “discontinuity layers” and other layers as “general layers”. The SLS system can identify the “discontinuity layers” and appropriately enhances the preheat temperature to achieve intelligent control of the preheat temperature. Fig. 2 shows the comparison in deformation between the SLS parts made without and with self-adaptive preheating. It can be found that the self-adaptive preheating method can greatly reduce the deformation of the overhang parts.

Figure 2. Deformation of the overhang parts in SLS: (a) parts made without self-adaptive preheating; (b) parts made with self-adaptive preheating

2.1.2 Multi-laser beams scanning system

For a large-scale laser sintering equipment, the traditional single laser scanning system usually induces great decrease in part accuracy and fabrication efficiency. Consequently, we develop multiple laser beams scanning system to make the laser sintering process more efficient and increase part accuracy. To realize the cooperative work of multiple lasers, data processing software with the ability of optimized segmentation treatment of multiple laser beam synchronized scanning pattern has been developed. Fig. 3 shows the scanning processing of two-laser beam scanning systems. The two scanning systems work collaboratively to finish the building of the impeller part. Each laser will scan approximately 50% of the cross section area.

Figure 3. Schematic illustration of multi-laser beam scanning process

Fig.4 shows the schematic of scanning task allocation for the multi-laser beam scanning process. We realizes the uniform segmentation of the whole part by segmenting each layer into two equal

regions for the two laser systems, thus achieving the scanning task uniform allocation for multi-laser systems.

Figure 4. Schematic illustration of scanning task allocation for multi-laser beam scanning process

2.1.3 Large-scale SLS system

We successfully developed and commercialized HRPS series large-scale laser sintering systems with effective building volumes of $1400 \times 700 \times 500 \text{ mm}^3$ and $1400 \times 1400 \times 500 \text{ mm}^3$ after developing the key techniques such as uniform control of preheating temperature field and multi-laser scanning system. The large-scale laser sintering system as shown in Fig. 5 is equipped with a four-laser scanning system and has an efficient building volume of $1400 \times 1400 \times 500 \text{ mm}^3$ and part accuracy of $\pm 0.2 \text{ mm}$ ($\leq 200 \text{ mm}$) or 0.1% ($> 200 \text{ mm}$). It can process various kinds of powdered materials including polymer and composite powders, and resin coated Sands, metal and ceramics powders. Fig.6 (a) shows the large-sized complex sand mould (core) fabricated by the SLS system with the maximum size of 960 mm, and Fig.6 (b) shows the merlion model from NTU by using the large SLS equipment.

Figure 5. HRPS VII type laser sintering system with large processing chamber developed by Huazhong University of Science and Technology, China

Figure 6. (a) Large-sized complex sand mould (core), the maximum size of 960 mm; (b) Merlion model from NTU.

2.2 High performance materials

At present, several thermoplastics such as polycarbonate (PC) (Ho et al., 1999), polystyrene (PS) (Dotchev et al., 2007), and nylon (PA) (Caulfied et al., 2007) are proved to be suitable for the SLS process. However, the mechanical properties of polymer SLS parts are lower than those of conventional injection moulding parts due to the existing pores. When the sizes of SLS parts are enlarged to more than 1000 mm, they will be easy to be broken during the moving process after building and post processing for the poor mechanical properties. Therefore, it is very necessary to prepare new materials with high mechanical properties for the large-scale equipment. We have

developed some high performance materials for the large-scale SLS process, such as High strength material for making investment casting pattern (Yang et al., 2009) and nylon coated composites powders (Yang et al., 2009; Yan et al., 2009; Yan et al., 2009).

2.2.1 High strength material for making investment casting pattern

During the dewaxing process, the SLS pattern material should burn out completely without leaving any residue, which may be detrimental to castings. Wax is the most frequently used material in investment casting for its thermal properties; unfortunately, the wax product may result in large geometry distortion in the SLS process. Nowadays, polystyrene (PS) is widely used for making investment casting patterns using SLS (Hock et al., 2003). However, PS is not suitable for making thin-walled parts or delicate structure parts due to the low mechanical properties of PS SLS parts. Therefore, we adopt high impact polystyrene (HIPS), a polymer blend of PS toughened with polybutadiene rubber, as an SLS material to make the investment casting patterns with good mechanical properties.

Table 1 Mechanical properties of SLS green and post-processed parts

	Tensile strength / MPa	Elongation/ %	Young's Modulus / MPa	Flexural strength / MPa	Impact strength / (KJ/m ²)
PS green parts	1.57	5.03	9.42	1.87	1.82
PS post-processed parts	4.34	5.73	23.46	6.89	3.56
HIPS green parts	4.59	5.79	62.25	18.93	3.30
HIPS post-processed parts	7.54	5.98	65.34	20.48	6.50

Figure 7. SEM micrographs of HIPS SLS green and post-processed parts. (a) HIPS green part; (b) HIPS post-processed part

The mechanical properties of PS and HIPS are listed in Table 1. The mechanical properties of HIPS specimens are much better than those of PS specimens. For instance, the flexural strength and Young's modulus of HIPS SLS green parts are 18.93 MPa, 62.25 MPa respectively, which are much higher than those of PS SLS green parts. Compared to PS, the particle bonding of HIPS powder is easier because of the viscous flow of rubber in it. This property causes the sintered HIPS specimens to have a more compact microstructure, and it results in better mechanical properties than PS specimens and suitable for making thin-walled and delicate structure parts.

Although the mechanical properties of HIPS for SLS parts are considerably better than those of PS, it is not sufficient for the application for investment casting of complex and large thin walled parts. Furthermore, its void fraction is 52.8% (Fig.7 (a)) and the surface is very rough and covered with powder that can easily be removed. Therefore, post-processing – infiltrating with wax – is discussed in this study. When the SLS parts are immersed in the melting wax, the melting wax would infiltrate the SLS parts through capillarity action. After post-processing, most of the void is filled with wax, and the voids fraction is decreased from 52.8% to 8.1% (Fig.7 (b)). As shown in Fig.7 (b), although there are some voids and naked HIPS particles, most of the HIPS particles are well wrapped by wax. It indicates that wax shows good bonding with HIPS because both of them are non-polar materials. Compared with the properties before post-processing, the mechanical properties are significantly improved (Table 1). The tensile strength and impact strength increased 64% and 97%, respectively.

In order to determine the ash content, gravimetric determination was employed. The process is shown as following: increase temperature to 50 °C, maintained at this value for 2 h and subsequently natural cool to room-temperature. Finally, the resulting ash contents of PS and HIPS are both 0.3%, which is acceptable for the investment casting process.

2.2.2 Nylon coated composite powders

Polyamide (PA), also termed nylon is proved to be suitable for the SLS process to directly make near-fully dense plastic parts, and have been widely used as SLS materials. However, pure nylon parts made by SLS often possess lower mechanical properties, especially impact strength, compared with those of conventional compression molded parts due to small portion of porosity. For this reason mentioned above, many efforts have been made to prepare the nylon based composites to enhance or tailor some properties of its SLS parts for various applications. At present, nylon-based composites filled with micron/nano-scale particles, such as glass beads (Childs et al., 2001; Chung et al., 2006), silicon carbide (SiC) (Hon et al., 2003), and aluminum powder (Mazzoli et al., 2007), have been developed for SLS. However, these nylon based composite powders for SLS process were mainly prepared by mechanically mixing neat nylon powders and reinforcement powders. Unfortunately, when either reinforcement powders have very small particle sizes (e.g., below 10µm) or there exist big differences in densities between neat nylon powders and reinforcement powders like metal powders, it is very difficult to mix the two powdered materials uniformly by this method. As a result, the reinforcement effect of these fillers on nylon SLS parts is limited.

Based on the previous works, we successfully developed a dissolution-precipitation process was to prepare PA based composite powder for SLS. Filler particles were first dispersed uniformly in the PA alcohol solution by ultrasonic oscillation and stirring constantly at about 160°C. Then, while the mixture was cooled gradually, PA crystallized taking the filler particles as heterogeneous

nuclei and the PA coated composite powders were formed gradually. As a result, filler particles could be uniformly dispersed in the composite powder and its SLS parts. We used the dissolution-precipitation process to prepare the PA/carbon fibre (Yan et al., 2011), PA/aluminium (Yan et al., 2009) and PA/nanosilica (Yan et al., 2009) composite powders for SLS.

Figure 8. SEM micrographs of (a) carbon fibre, (b) nylon-12/carbon fibre composite powder, (c) fractured surface of SLS part (Yan et al., 2011)

Figure 9. (a) Mechanical properties and (b) thermal stability of the SLS parts are increased (Yan et al., 2011)

Fig.8 (a) shows the SEM micrographs of the surface modified carbon fibres. Fig. 8(a) reveals that the carbon fibre powder is comprised of small irregularly shaped particles and the fibres with different lengths ranging from about 20 μm to 100 μm , and the diameter of the fibres is about 7 μm . The SEM micrographs of the PA/carbon fibre composite powder is shown in Fig.8 (b). The composite powder has similar shape to the carbon fibres, and is comprised of the irregularly shaped particles and fibres with different lengths. But by comparing Fig.8 (a) and Fig.8 (b), it can be found that the surface of the composite powder is much different from that of the carbon fibres, and the carbon fibres are coated with a layer of PA, indicating that good adhesion is established at the interface between two materials and carbon fibres are well dispersed in the composite powder. After the flexural tests, SEM micrographs were taken of the fractured surfaces, as shown in Fig.8 (c). The fractured surface SEM image shows the fibre surface is coarse, and most of the fibres are coated by PA, indicating good adhesion between the fibres and the PA matrix.

The effect of carbon fibre content on the flexural properties of the PA/carbon fibre SLS parts is shown in Fig.9 (a). The carbon fibres can greatly enhanced the flexural strength and flexural modulus of sintered components, which are increases with increasing the carbon fibre content.

Fig.9 (b) depicts the TGA curves of the PA/carbon fibre composites. It can be found that carbon fibres can greatly enhance the thermal stability of PA.

Figure 10. SEM micrographs of (a) aluminium powder, (b) nylon-12/aluminium composite powder, (c) fractured surface of SLS part (Yan et al., 2009)

Fig.10 (a) and (b) show the SEM micrographs of aluminium powder and nylon-12/aluminium composite powder. It can be found that the aluminium particles are coated with a layer of nylon-12 resin; therefore, the aluminium powder is uniformly dispersed in the nylon-12 matrix. Fig. 4(c) shows the fractured surface of the SLS part made from the composites powder. The rough surfaces indicate the good interfacial adhesion between aluminium particles and nylon-12 matrix. The tensile strength, flexural strength and flexural modulus of the SLS specimens made from the nylon-12/aluminum powder increase by about 10.4, 62.1 and 122.3% respectively when the mass fraction of the aluminum powder is 50wt%, compared with pure nylon-12 SLS parts.

Figure 11. (a) SEM image of cryogenically fractured surface and (b) Mechanical properties of nylon-12/nano-silica composite SLS parts (Yan et al., 2009)

The nylon-12/nano-silica composite powder was prepared by a dissolution-precipitation process for the SLS process. Fig.11 (a) shows the SEM image of cryogenically fractured surface of the nylon-12/nano-silica composite SLS parts. It can be observed that the small and discrete nanosilica particles are homogenously distributed on a nanometer level in the PA12 matrix. Fig.11 (b) shows the mechanical properties of the composite SLS parts and pure nylon-12 SLS parts at different laser energy density. The tensile strength of the composite SLS parts is higher than that of pure nylon-12 SLS parts at the same laser energy density.

3 SLM equipment and high performance materials

3.1 Large-scale SLM system

With the similar process principal, SLM uses a higher laser power, which enables the full melt of metal powders, leaving the un-melted powder as supporters. Based on the SLM mechanism and the improved key technology of large SLS system, HRPM series of SLM machines have been developed. Recently, the large-scale SLM system shown in Fig.12 is equipped with double-laser scanning system and has an efficient building volume of $500 \times 250 \times 400$ mm³. It consists of fiber laser system, scanner system, cooling system, powder feeding and leveling system, build chamber, and controlling system. In order to compact the SLM machine, a new powder feeding system was developed and its principle is that the powder could be delivered by powder feeder above. The roller angle can be controlled with grooves and the volume of powder dropping into the workpiece forming chamber can also be controlled. The oxidation is an important phenomenon in SLM process, which is detrimental for SLMed part, leading to balling and pores. Aimed to resolve the problem, the SLM forming chamber could be pumped and filled with Ar₂ gas to prevent oxidation.

Figure 12. HRPM SLM machine developed by HUST

3.2 Materials for SLM

Similar to SLS, materials development is also another essential topic in SLM. In our laboratory, several kinds of alloys materials are processed by SLM, including stainless steel, Ni based alloy, Ti based alloy, Co-Cr and other materials. Gas-atomized 316L stainless powder as shown in Fig.13

(a) exhibits a spherical shape and very fine particle size. The nearly full density parts were fabricated and the tensile stress shows an improvement than the commercial 316L processed by traditional ways. As is shown in Fig.13 (c), small dimple fractures were found, showing a ductile fracture. It is found that high loose density is favorable for the SLM density. Moreover, the gas-atomized stainless steel powder has very low oxygen content than water-atomized powder, which facilitates the wetting ability. We have also developed rare materials for SLM process, such as W-Cu forming, which is shown in Fig.14. The properties of SLMed materials are listed in Table 2.

Figure 13. Images of 316L stainless steel: (a) powder; (b) microstructure of SLMed sample; (c) appearance of fracture

Figure 14. SEM image showing characteristic morphologies of starting metal powder

Table 2 Mechanical properties of SLM parts

Material	Density	Hardness	Elongation/ %	Tensile strength / MPa	
				X-Y	Z
SS 316L	99.9%	/	>9	620	668
Ni625	99%	HV343	/	1113	/
Ti6Al4V	99.5%	/	10.6	1346	/
AISI 420	99.5%	HRC47	<1	610	1050
Co-Cr	99.5%	/	7.6	1605	/

3.3 Applications

Based on the research work, some special functional parts were fabricated as shown in Fig. 15. The lattice structure was fabricated with a minimum wall thickness of 0.1mm. This component cannot be manufactured by traditional way. The oil drilling core and several kinds of blade were produced by SLM in few hours or days, showing a potential to process the difficult-to-machine material for the aerospace application. The injection mould with inner conformal cooling channels has been proved to increase the cooling efficiency by nearly 30%.

Nickel Alloy lattice structure (136mm long×20mm wide×25mm height, wall thickness 0.1mm)

Oil drilling core part

Hollow aeroengine blade

Impeller disc and fan blade

Mould with Conformal cooling channels and plastic part made from the mould

Figure 15. Metallic parts directly made by SLM

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