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Rapid prototyping manufacturing of silica sand patterns based on selective laser sintering

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Abstract

In recent years, rapid prototyping manufacturing technology (RPM) has gradually becoming matured, and has been widely used in the fabrication of functional and practical metal and ceramic components. However, researches on the selective laser sintering (SLS) of silica sands were very limited. Experiments on rapid prototyping manufacturing of silica sands were carried out based on SLS. Micro morphologies of the sintered patterns under different working conditions were observed with three-dimensional optical microscopy (OM). Influences of process parameters such as laser power, scanning speed, overlapping rate, laser beam diameter and powder mixture ratio on the dimension accuracy and sintered qualities were investigated systematically. It indicated that "stepping effect" and deformation of the sintered samples reduced through the decreasing of slicing thickness and the optimization of process parameters. Finally, qualified selective laser sintering silica sand patterns were obtained.

Keywords: Rapid prototyping manufacturing; SLS; Silica sand patterns; Sintered quality

1. Introduction

Selective laser sintering (SLS) is one of the important branches of rapid prototyping manufacturing (RPM) that integrates computer engineering, numerical control technology, laser technology and material processing technology. It was also one of the most significant breakthroughs in recent 20 years. In the processing of SLS, laminated additive manufacturing method can be utilized to fabricate three-dimensional arbitrary shaped components from CAD models without the involving of special tools and dies. Therefore, production flexibility and processing speed can be greatly improved, lead time and total cost can thus be reduced. Compared with other RPM technologies, a wide range of materials such as organic polymers, waxes, metals and ceramics can be used in SLS, the post processing is simple, and it is less time consuming. As a result, it has been highly focused since the invention in the end of 1980s and has been rapidly developed [1–5].

Presently, the hot researching spot in the field of selective laser sintering is mainly focused on the processing of metals and ceramic materials, and notable achievements have been achieved. However, as a kind of abundant and cheap material, researches on the SLS of silica sand were still very limited [6–8]. In this paper, rapid prototyping manufacturing of silica sand patterns based on selective laser sintering was studied. Effects of process parameter on the forming qualities were investigated combining experimental studies and microanalysis methods, and qualified silica sand patterns have been obtained.

2. Experimental of selective laser sintering

2.1. Experimental system and materials

The experimental system consisted of a 3 kW cross-flow CO_2 laser machine, a self-designed and built powder layering device, a set of computational modeling software and SIEMENS numerical control system. The accuracy of the numerical control system was 0.1 mm. The principle of selective laser sintering system is shown in Fig. 1. In the SLS process, powders were scanned along the preplanned tracks by laser beam according to the CAD model of the components. After scanning of one layer, the piston was lowed down for a distance of one layer thickness. Then the powders were preplaced on the previous sintered layers with the powder layering roller, and finally the whole silica sand pattern can be sintered by scanning layer by layer.

The experimental materials used were self-prepared silica sand-phenol formaldehyde resin (PF resin) compounds. The main components of the silica sands were SiO_2:99%, Al_2O_3:0.22%, and micro-content of TiO_2, melting point is 1750 °C, the bonding agent was PF resin with grain size of 200 meshes and softening point of 105–115 °C, the solidified agent was 8–12% methenamine.

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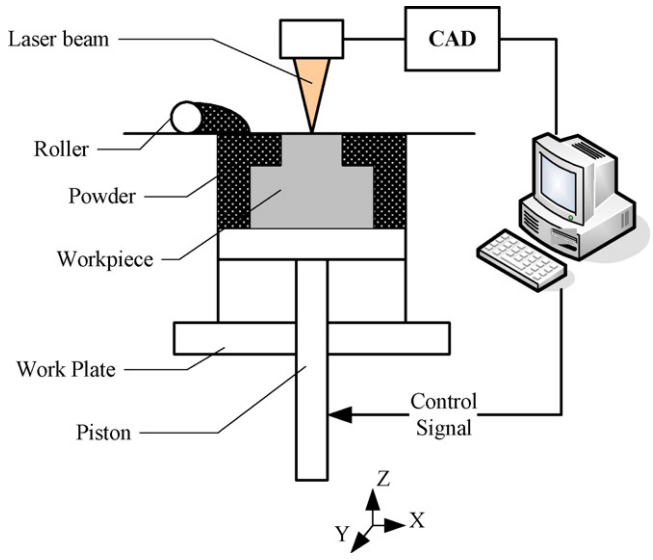

Fig. 1. Principle of the SLS system.

2.2. Experimental methods

In order to investigate the influences of process parameters on the quality and dimension accuracy of the sintered samples, the length, width and height of the multi-track laser sintered samples were respectively calibrated as L, W and H. The effects of laser power P, scanning speed F, overlapping η, laser beam diameter D and powder mixture ratio Φ on the sintered qualities and accuracy were studied respectively under conditions that other parameters were fixed, the experimental results were average values of multiple experiments. After the sintering of the samples, micro morphologies of the surface under different working conditions were observed under KEYENCE three-dimensional microscopes.

3. Results and discussion

3.1. Effects of laser power on the sintering quality

The forming mechanism of selective laser sintering silica sands lies in the absorption of laser beam energy. Under the heating action of laser beam, bonding agents are softened and molten, after the solidification, silica sand grains are inserted in the bonders and constituted a solid state bonding skeleton. Because the softening point of the silica sand is rather lower, only about 110 °C, and the optimized heating hardening temperature is about 250 °C, the required power is quite lower. At the same time, because the power of the laser machine jumps in a range of several watts, which leads to an obvious error while analyzing the influences of laser powers. On the other hand, because the electric current is relatively steady, it can be used as the reference value of laser power. It has been observed from the experiments that at an electric current of 0.8 A, bonding agents PF resin has not been completely melted; at an electric current of 1.0 A, the sintered effect was the best; while the electric power increases to a value of 1.2 A, the surface of the sample was car-

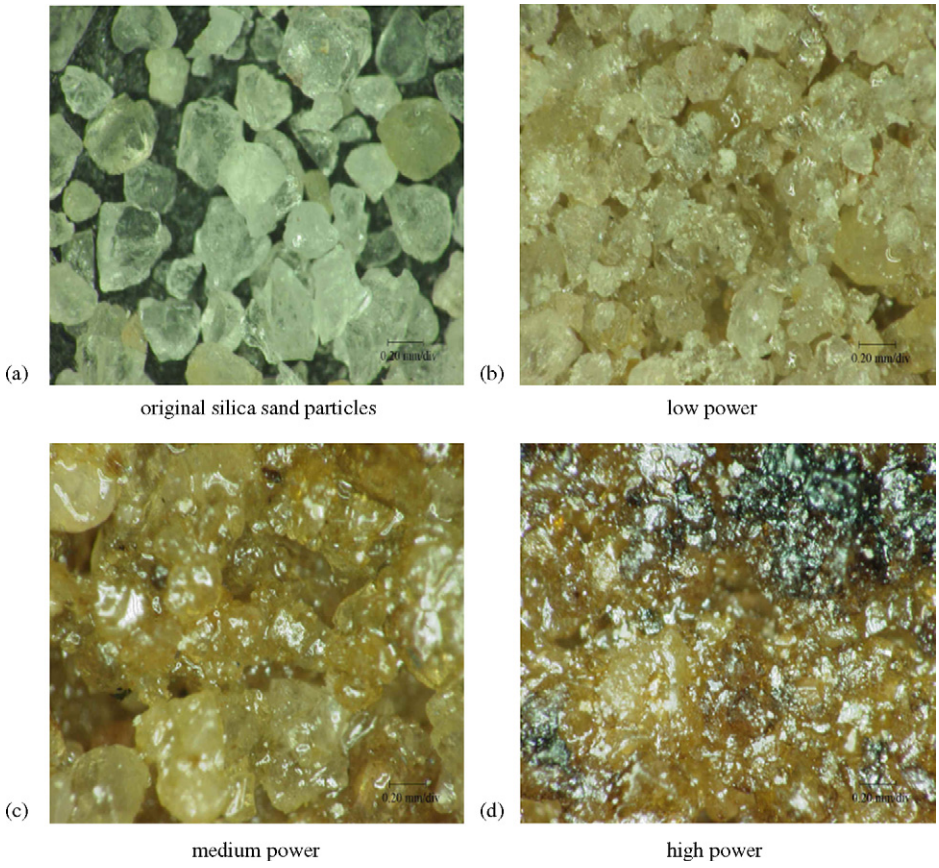

Fig. 2. Effect of laser power on the micro morphology of the sintered samples: (a) original silica sand particles (b) low power, (c) medium power, and (d) high power.

bonized and presented a black color. Therefore, the optimized electric current under experimental conditions was 1.0 A.

Fig. 2 shows the effects of different laser powers on the micro morphologies of the sintered samples. Fig. 2(a) shows the morphology of the original silica sands. It showed that the grains of the original silica sands were basically uniform regular semitransparent crystals presenting on a color of milk white and pale yellow. After the mixing and pressing, the outside of the silica sands were packaged by the bonding agents, the gaps of the silica sand grains were filled with bonders. Fig. 2(b) is the micro morphology under lower power, it can be seen that the surface of the sample presents a color of pale yellow under low power, parts of the binders are not fully melted, and the bonding strength is not enough. Under medium power, the surface of the sample is in a deep brown color, the silica sand grains are mosaicked in the solid binders and forms a semitransparent bonded body with an ideal sintered effect, as shown in Fig. 2(c). Fig. 2(d) shows the sintered surface under higher laser power, because the energy is too large, local areas on the surface present black brown colors and the binders has been carbonized.

3.2. Effects of scanning speed F on the dimension of the sintered samples

Fig. 3 indicates the influence of scanning speed on the dimension of the sintered samples at a laser beam diameter 3 mm, overlapping width 0.5 mm, laser power 12 W, and powder ratio of silica sands and PF resin 14:1. With the increasing of scanning speed, the length, width and height of the sample decreases gradually. The reason of this result is that with the increasing of the scanning speed, the dwelling time of the laser beam on the scanning spot shortened correspondingly, while the laser power is constant, the actual input energy in a unit time reduces, and the heat affected zone has also been reduced, which result in a dimension lessening of the sample.

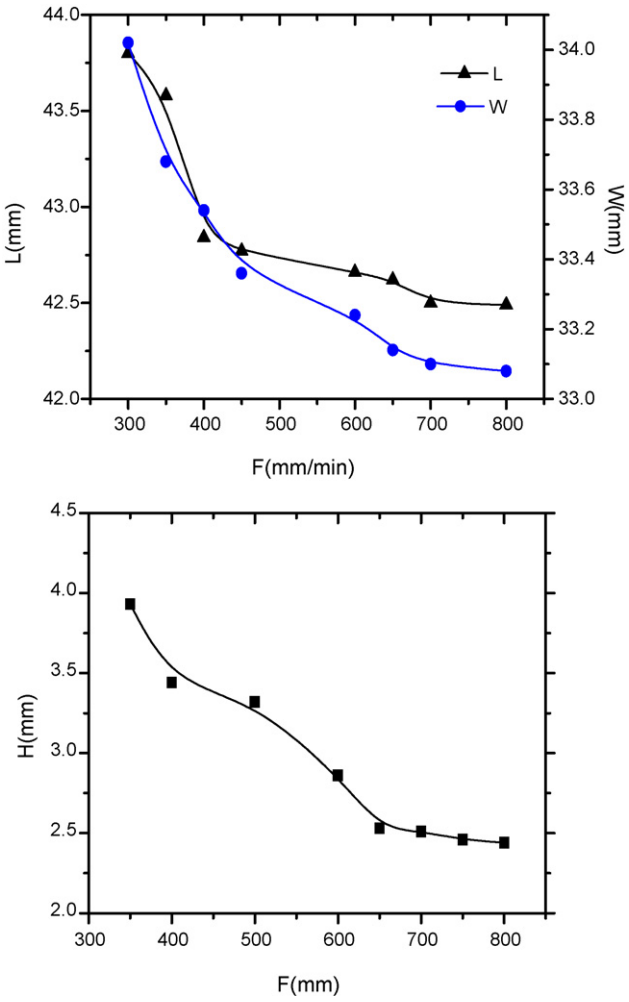

Fig. 3. Effect of scanning speed on the dimension of the sintered samples.

3.3. Effect of overlapping η, laser beam diameter D and powder mixture ratio Φ on the height of the samples

In the experiments, laser beam diameter D was set to 3 mm by adjusting of the defocusing amount, overlapping η of adjacent scanning tracks varied in the range of 0.5–2.0 mm, laser power P was 12 W, powder ratio Φ was 11:1, and scanning speed F was 650 mm/min. With the increasing of overlapping, sintering depth increased. While the overlapping was increased, the absorption of laser energy increased, more quantities of binders were melted, and the depth of the softened binders increased. Under conditions that other experimental parameters were fixed, laser beam energy density decreased with the increasing of laser beam diameter, and the sintered depth reduced rapidly, as shown in Fig. 4.

Fig. 4 also shows the relationships between powder mixture ratio Φ and the sintered dimensions under condition of laser spot 3 mm, laser power 12 W, overlapping 1.1 mm and scanning speed 650 mm/min. It can be seen that with the increasing of Φ, the length, width and thickness of the sample varies slightly, but not very significantly. That is with the increasing of the bonding agents, the dimensions of the sintered samples slightly increase. Due to the reduction of the bonding agent contents, the connection bridges among silica sand powders reduced, the softened and melted areas and the depth of the mixed powder decreased correspondingly. Therefore, the compressive strength of the sintered samples can be enhanced with higher binder content, but too much bonding agents will result in a large amount of deformation and contraction, which results in the fluctuation of the dimensions. The solidification contraction of PF resin results in a difference between actual dimensions and the designed ones of the sintered samples, but there still have some rules to be followed. The powder mixture ratio of the subsequent experiments is selected as 11:1.

3.4. Post processing of the sintered samples and quality analysis

Before the post processing, there are residual unmelted bonding powders in the selective laser sintered samples, and the distribution of bonding agents is not homogeneous, the strength of the samples is low, and thermal holding process is required. The sand patterns can only be used in casting after the hardening

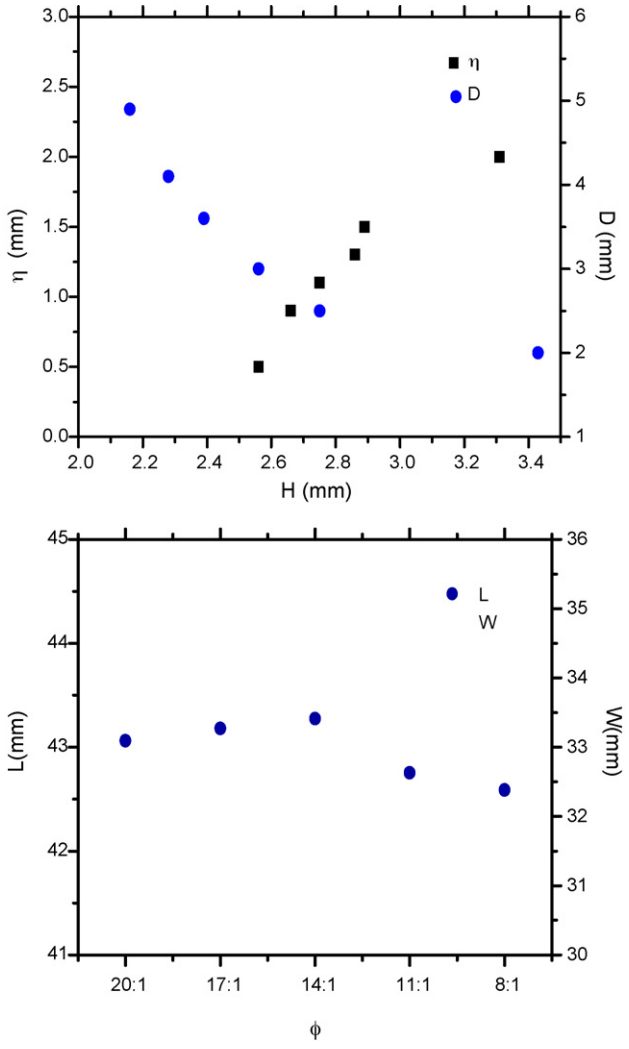

Fig. 4. The relation of overlapping, spot size and powder ratio to the dimension of the sintered samples.

Fig. 5. Sand patterns sintered by selective laser sintering.

process, in which the congregating phenomena of the bonding agent can be eliminated, water and gasifiable matters can be volatilized, and binders can be uniformly distributed when the sintered sample is holding at about 250 °C for 30 min. In order to improve the strength of the sintered samples without carbonization, the post processing temperature should not surpass 300 °C. Because selective laser sintering is a laminated material additive manufacturing process, the slicing thickness and process parameters have a significant effect on the quality of the not controlled properly and the "stepping effect" will appear. The dimension accuracy and surface finish of the samples will be greatly affected. Simultaneously, in the processing of SLS, due to the non-uniform heating and contraction, deformation is liable to occur. To avoid these defects and improve the surface finish, the slicing thickness should be thin enough, and reasonable process parameters should be selected. The single layer thickness also has an effect on the property of the sintered components. Thin slicing layer will result in a higher dimensional accuracy and mechanical strength, but the manufacturing time will be prolonged. If the layer is too thin, uniformity and compactibility of powder layering will become difficult. Moreover, laser power density is decided by the laser power and spot size, and heating temperature and period of the powders are depended on laser power density and scanning speed. Under conditions of low power density and rapid scanning speed, parts of the powders have not enough time to melt completely, and the strength of the sample is lower. Whereas, the powder temperature is excessively higher, the binding agents will be scorched and gasified, and the sintered surface will become rough, bonding properties between layers and the sintering quality will be reduced.

According to the above analysis, it is concluded that better sintering effects can be obtained with a medium laser power and lower scanning speed. The optimized process parameters are as follows: electric current 1.0 A, scanning speed 650 mm/min, laser beam diameter 3 mm, overlapping 0.5 mm and powder mixture ratio 11:1. Sand patterns sintered with previous parameters are shown in Fig. 5.

4. Conclusions

Selective laser sintering of silica sands has the characteristics of high flexibility, shorter lead time, lower cost, procedure centralization and forming without dies. It is especially suitable for

the development of complex shaped castings and the production of single and small lot pieces.

Process parameters have important effects on the property and accuracy of the sintered samples. With appropriate input laser power, powder ratio and overlapping, the surface accuracy and dimension precision can be improved, the interlayer bonding strength and the mechanical strength of the whole components can also be improved.

Bonding agents can be uniformly distributed and the strength of the samples can be enhanced with the post processing and holding, but the holding temperature cannot surpass 300 °C. Forming precision of the samples can also be improved by the decreasing of slicing thickness and the optimization of process parameters.

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