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Direct laser sintering of a silica sand

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Abstract

As an application study of rapid prototyping, commercially available silica sand was successfully direct-laser-sintered in a self-developed high-temperature laser sintering equipment. The mechanism of powder-state sand becoming a solid state block during the laser sintering process was disclosed by scanning electron microscope (SEM) and energy dispersive X-ray (EDX) analysis on sand particles and sintered samples. The effect of process parameters to the accuracy, strength and surface finish of sintered parts was investigated and thus a set of optimal parameters has been obtained for the sand sintering process. The feasibility of using this material and process to build casting moulds for metal casting was also investigated and discussed.

Keywords: Rapid prototyping (RP); Direct laser sintering; Silica sand; Casting

1. Introduction

As one of the most developed rapid prototyping (RP) processes, selective laser sintering (SLS) has been widely used in the manufacturing area of modern industry, either for functional prototyping or for actual part building, even for rapid tooling and for mid-volume production. When compared with other RP processes, the distinguished advantage of SLS is that a wide range of materials, from low melting point (such as wax) to high melting point materials (such as metals or ceramics), can be sintered in the process. Generally, SLS is divided into two categories: the direct process and the indirect process. In the indirect SLS process, the employed material is constituted of particles coated with relatively lower melting point polymer acting as a binder, and the laser beam actually melts the polymer binder, which then 'glues' the other particles together. The polymer binder should be thermally removed and the part should be treated in a post-process for a fully consolidated and higher density. In the direct process, the laser beam directly sinters the raw material into final parts, and no post-process is needed [1–3].

The research work of SLS development now focuses on the direct SLS, especially for the metal and ceramic materials. The purpose of direct SLS is to fabricate functional metal or ceramic parts in a single process, much cost and time could be saved compared to the conventional processes. Hence, the direct SLS is regarded as 'rapid manufacturing' more than 'rapid prototyping'. Many literature on this topic has been published in recent years [4–9]. For direct laser sintering of silica sand, although the material could be regarded as a kind of ceramics, very little research work, especially with engineering application, has been reported so far. The most related work was reported on the SLS of Zirconium Silicate by Klocke et al. in 1998 [10].

This paper presents the development of direct laser sintering of silica sand. The experiments and results are reported on the material, the process and the application of this direct SLS.

2. Experimentals

2.1. Experimental equipment

For the purpose of direct laser sintering of metals and ceramics, an experimental equipment has been self-developed. A 200 W CO_2 laser has been used in this

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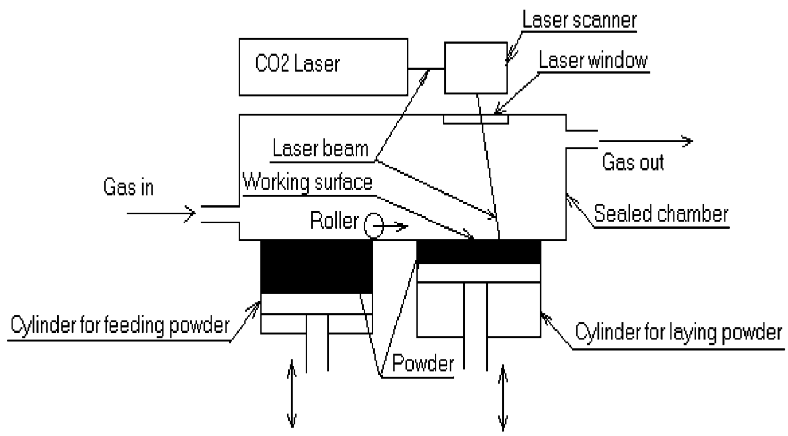


Fig. 1. Experimental equipment.

equipment. Actually, the power of 200 W is not enough for melting or sintering high-melting point materials of some metals and ceramics, hence a pre-heating device is built in the equipment, which can pre-heat the powder bed of materials up to 400 °C. For preventing the materials from oxidation at a high temperature in the sintering process, the working space is sealed in a gas chamber, which could be filled with Nitrogen or Argon. A secondary material feeding system is also built in the equipment, making it possible for multiple material sintering. The layout of this equipment is shown in Fig. 1.

The various materials from polymers, metals to ceramics have been successfully sintered in this equipment. The direct laser sintering of silica sand is one example of these successful cases.

2.2. The material

The silica sand is round grain, washed and graded to AFS 90 (100–120 μm). This type of silica sand is commonly used in foundry industry to build ceramic shell or core for metal casting. It is generally sintered at a temperature up to 1200 °C in a furnace. For the case in direct laser sintering, the sand was ball-milled to a finer grain size under 50 μm.

In order to study the mechanism of powder-state sand becoming a solid state during the laser sintering process, the original sand particle and sintered sand sample were analysed by scanning electron microscope (SEM) and energy dispersive X-ray (EDX) analysis.

2.3. Direct laser sintering experiments

For sintering this type of silica sand, a set of parameters had been tried and some of them have quite good results in sintering qualities such as strength, surface finish, etc. In order to systematically analyse the effect of process parameters to the qualities of sintered parts, a series of experiments were designed in the following three aspects:

1. The effect of process parameters to the strengths of sintered parts: As the sand is a kind of a fragile material and the major use of this kind of sand sintering is to build casting mould, the compression

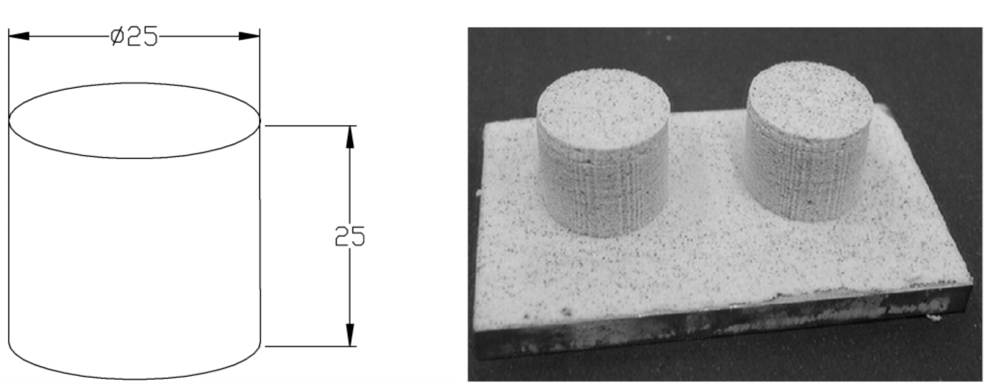


Fig. 2. Samples for measuring compression strength of sintered parts.

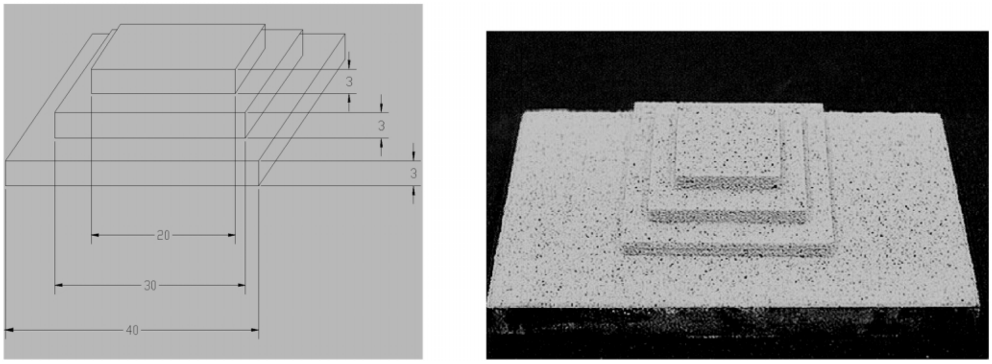


Fig. 3. Sample part for measuring accuracy of sintered parts.

strength is mainly considered in our experiment. The sample for measuring compression strength is shown in Fig. 2. The compression strengths of samples under different parameters were measured and the effect of process parameters to the strengths of sintered parts was obtained.

2. The effect of process parameters to the surface roughness of sintered parts: The surface roughness is an important factor to the quality of sintered casting mould. In order to improve the surface quality, the effect of process parameters to the surface roughness was investigated and thus optimum parameters could be obtained.
3. The effect of process parameters to the accuracy of sintered parts: The direct laser sintering of sand is a thermal process. The heat affected zone (HAZ), the distortion and the shrinkage during the process may seriously affect the shapes and sizes of sintered parts. These effects also depend on the process parameters. Experiments were designed to investigate the effect of process parameters to the accuracy of sintered parts. The sample for measuring accuracy is shown in Fig. 3.

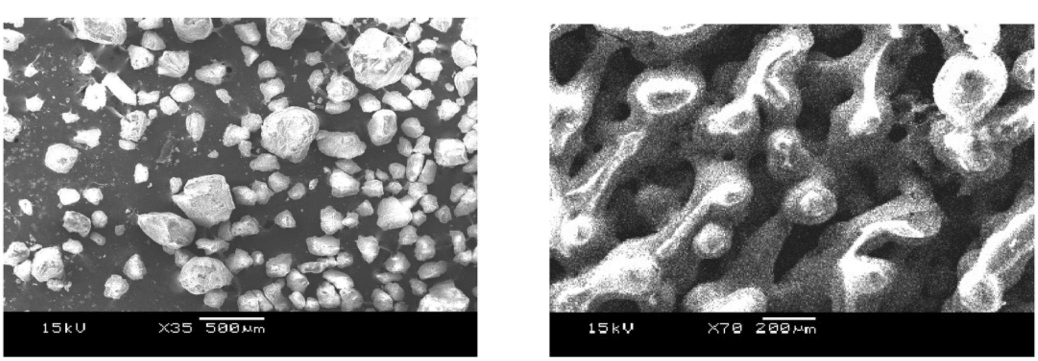
2.4. Casting mould building

For the direct laser sintering of silica sand, no polymer was used in the whole process. The material is a kind of ceramics and can stand at high temperature up to 1200 °C. The application of sand sintering is commonly considered as metal casting, which could be used to fabricate metal parts on mid-volume production. The metals used in the casting include aluminium, iron, etc. As an application experiment, a couple of sand mould was built in our direct laser sintering equipment using optimum parameters.

3. Results and discussions

3.1. The SEM and EDX analysis of original sand particles and sintered sand sample

The SEM of original sand particle is shown in Fig. 4a, in which the shape of the particle is shown as a regular crystal. After laser sintering, the particles are bound together as shown in Fig. 4b. From this SEM picture, it is shown that the particles are not fully melted



(a) SEM of original sand particles (b) SEM of sintered sand sample

Fig. 4. SEM of original sand particles and sintered sand sample. (a) SEM of original sand particles. (b) SEM of sintered sand sample.

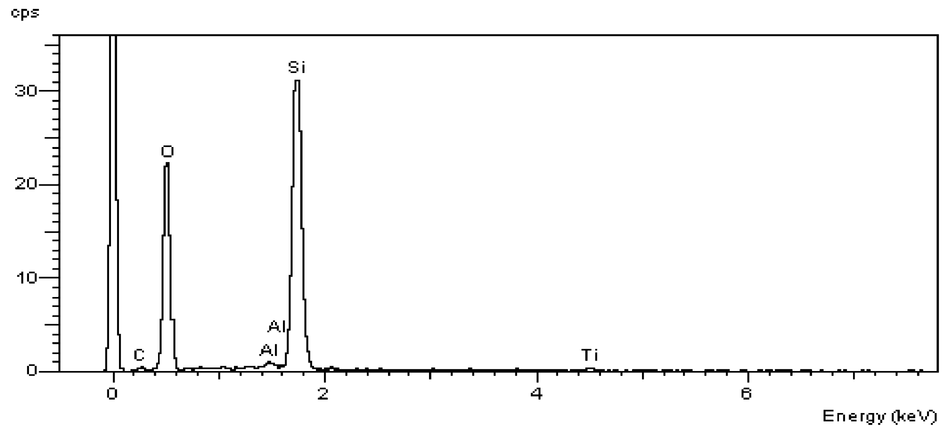
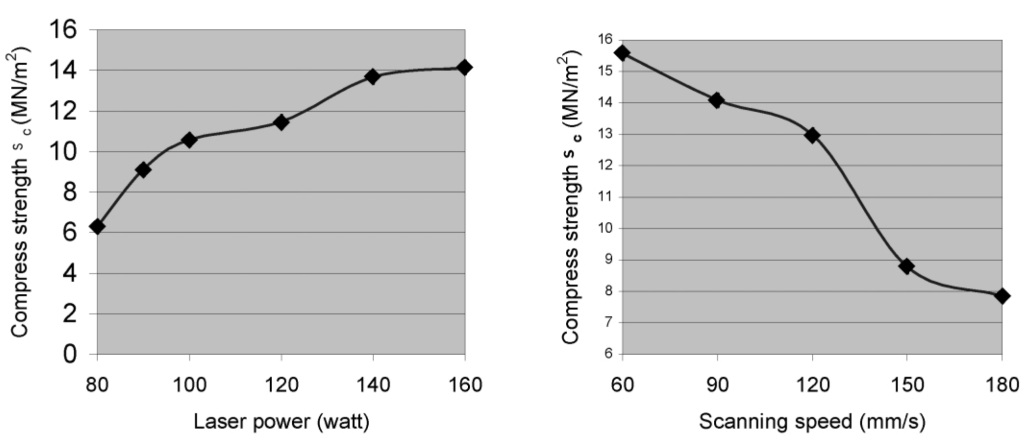


Fig. 5. EDX analysis of sintered sand sample.

and sintered together; only the surfaces of particles are melted and connected through 'bridges'. The most part of the sand particle is not melted and is kept as solid state during laser sintering. This phenomenon could be explained with two reasons. The first one is that, the action time of laser heating sand particle is very short, only the surface of the particle can absorb the laser energy and be melted in such a short time. The second one is that, the melting point of the surface of the particle is lower than that of the core of the particle.

The further explanation of the mechanism of this sand sintering can be obtained from the EDX analysis of sintered sand sample shown in Fig. 5. The result of EDX analysis shows that the main content of the sample is SiO_2 (elements Si and O), and a very low percentage of Al_2O_3 (elements Al and O) exists. The inclusion of Al_2O_3 can act with SiO_2 to create some kind of salt eutectic, which has much lower melting point than that of SiO_2. Therefore, the inclusion of Al_2O_3 greatly reduces the melting point of the surface of sand particle, which enables it easier to be melted than the core of the particle.

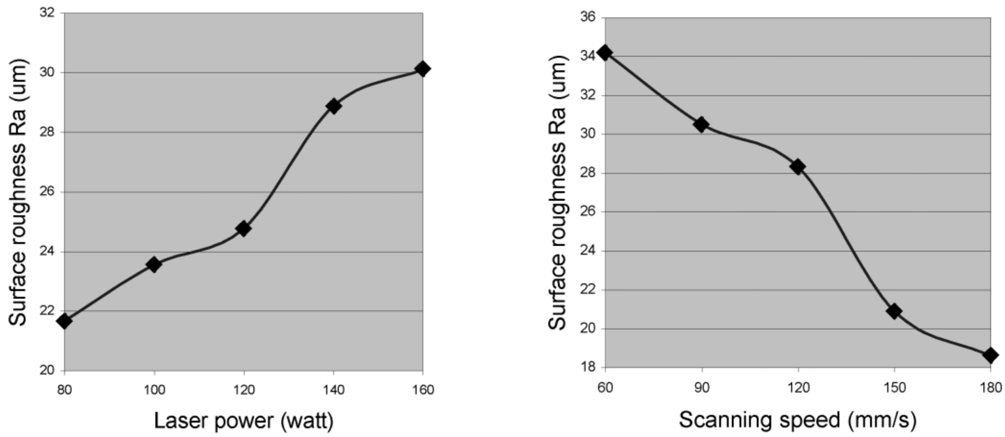
Summarily, the mechanism of laser sintering of silica sand can be explained as follows: the existence of very low percentage of Al_2O_3 acts as an inclusion, which greatly reduce the melting point of the surfaces of sand particles, and thus the surfaces become easily melted under laser heating. The sand particles bind together



(a) Compression strength of sintered parts vs. laser power (Scanning speed 120mm/s)

(b) Compression strength of sintered parts vs. laser scanning speed (Laser power 120 watts)

Fig. 6. Effect of process parameters to the compression strength of sintered parts. (a) Compression strength of sintered parts vs. laser power (Scanning speed 120 mm/s). (b) Compression strength of sintered parts vs. laser power scanning speed (Laser power 120 W).



(a) Surface roughness of sintered parts vs. laser power (Scanning speed 120 mm/s)

(b) Surface roughness of sintered parts vs. laser scanning speed (Laser power 120watts)

Fig. 7. Effect of process parameters to the surface roughness of sintered parts. (a) Surface roughness of sintered parts vs. laser power (Scanning speed 120 mm/s). (b) Surface roughness of sintered parts vs. laser scanning speed (Laser power 120 W).

through the liquid surfaces and then solidify after the laser beam is moved away and the temperature lowers down.

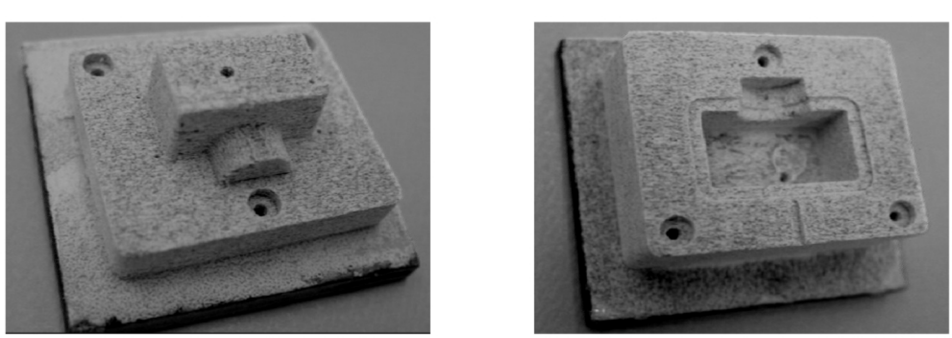
3.2. The effect of process parameters to the strength of sintered parts

The direct laser sintering of silica sand is expected to be used in casting mould, hence the compression strength of sintered parts is mainly concerned in our experiment. The major process parameters are laser power and scanning speed. When the scanning speed was kept at a constant of 120 mm/s, the effect of laser power to the compression strength of sintered parts is shown in Fig. 6a. Similarly, when the laser power was set at a constant of 120 W, the effect of scanning speed to the compression strength of sintered parts is shown in Fig. 6b.

From Fig. 6, it can be seen that the compression strength of sintered parts increases when the laser power increases, and decreases when the scanning speed increases.

3.3. The effect of process parameters to the surface roughness of sintered parts

When the scanning speed was kept at a constant of 120 mm/s, the effect of laser power to the surface roughness of sintered parts is shown in Fig. 7a. Also, when the laser power was kept at a constant of 120 W,



(a) Core (b) Cavity

Fig. 8. Casting mould: (a) Core and (b) Cavity.

Table 1
Results of accuracy measurements

Process parameters	X direction (mm)				Y direction (mm)			
	2.00	3.00	4.00	Average error	2.00	3.00	4.00	Average error
Laser power 80 W Scanning speed 60 mm/s	2.41	3.39	4.41	0.403	2.40	3.41	4.43	0.413
Laser power 100 W Scanning speed 90 mm/s	2.32	3.31	4.29	0.317	2.31	3.29	4.31	0.303
Laser power 120 W Scanning speed 120 mm/s	2.26	3.22	4.25	0.243	2.24	3.23	4.24	0.237
Laser power 140 W Scanning speed 150 mm/s	2.20	3.16	4.19	0.183	2.18	3.15	4.17	0.167
Laser power 160 W Scanning speed 180 mm/s	2.12	3.14	4.15	0.137	2.13	3.12	4.10	0.117

the effect of scanning speed to the surface roughness of sintered parts is shown in Fig. 7b. It follows that the surface roughness of sintered parts increases when the laser power increases, and decreases when the scanning speed increases.

3.4. Results of accuracy experiments

Accuracy samples (shown in Fig. 3) were sintered using different process parameters. The results of accuracy measurements are shown in Table 1.

The results show that the absolute errors of actual sizes of sintered parts to the design sizes are between 0.1 and 0.5 mm depending on different parameters. The match of lower laser power and lower scanning speed results in a bigger error. However, for a certain set of parameters, the errors are relatively stable, for example, the errors are between 0.22 and 0.26 mm under the parameters of 120 W laser power and 120 mm/s scanning speed. Therefore, it is possible to get an error data corresponding to a certain set of process parameters and this error data could be compensated by the control software.

3.5. Results on casting mould building

Based on the above experiments regarding to the accuracy and qualities of laser sintering sand parts, optimum parameters were selected to build a set of casting mould as shown in Fig. 8. The parameters are as follows:

Scanning pattern: raster.
Laser power: 120 W.
Scanning speed: 120 mm/s.
Scanning space: 0.2 mm.
Layer thickness: 0.15 mm.

The result shows that the sintered mould has a good strength and surface finish.

4. Conclusions

Based on the above experimental works, conclusions can be obtained as follows:

1. The surface of the sand particle became easily melted under the laser beam because of the existence of the inclusions such as Al_2O_3. The sand particles bind together through the liquid surfaces and then solidify during the direct laser sintering.
2. The compress strength and surface roughness of sintered parts increases when the laser power increases, and decreases when the scanning speed increases.
3. The errors of actual sizes of sintered parts to the design sizes are some big and changed accordingly by different parameters. However, it is stable under a certain set of parameters and could be compensated by the control software.
4. Some successful work has been done on using direct laser sintering of silica sand to build casting mould.

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