Effect of 316L stainless steel powder size distribution on selective laser melting process

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Abstract: The product quality of selective laser melting (SLM) is closely related to the alloy powder size distribution. The small voidage of fine-sized alloy powder bed is beneficial to improve the density of SLM product. While, the fine-sized alloy powder would result in the poor powder spreading uniformity in the SLM equipment, which leads to the formation of holes in the SLM product. In this work, the 316L stainless steel powder was prepared by a vacuum atomization furnace and sieved into a coarse-sized distribution and a fine-sized distribution. Then, the coarse-sized powder and the fine-sized powder are mixed according to different ratios. The results show that, under the condition of same SLM parameters, the density and strength of the SLM sample gradually decrease, with the increasing amount of fine-sized powder. The main reason for this phenomenon is that the fine-sized powder, with the large specific surface, is easy to bond with the coarse-sized powder. It reduces the fluidity of powder, resulting in the pores and cracks during the SLM layering process. Furthermore, the addition of fine-sized powder to the coarse-sized powder results in a decrease in the elongation of SLM sample. However, with the increase of the addition amount of the fine-sized powder, the residual stress is released due to the formation of a large number of cracks and pores, so that the elongation of SLM sample is slightly increases.

1. Introduction
Recently, an additive manufacturing method (3D printing technology), a supplement to the traditional manufacturing industry, has gained a lot of attentions due to the advantages of rapid preparation of complex parts [1,2]. With the improvement of 3D printing equipment, the range of 3D printing raw materials has been expanded from organic materials with low melting points to metal materials with high melting points, which extends its application range to the fields of aerospace, automobile and mold manufacturing [3,4]. Selective laser melting (SLM) is a mainstream technology of 3D printing with metal materials [5,6].

There are two major applications in the field of mold manufacturing for the SLM process. One is the cooling mold whose cooling channels frees from cross-drilling restrictions. The internal channels can be designed to be closer to the cooling surface of the mold, with a smooth corner, faster flow and increased efficiency of heat transfer to the coolant. The other is the tire base mold with multi-angle and multi-radiation, which can adapt to the complex environment of wind and snow for different types of
vehicles. Currently, the amount of stainless steel powder, such as 316L, used in molds accounts for 17% of the global 3D printing metal materials. Although a lot of researches on the optimization of SLM process have been carried out [7-9], few works focus on the effect of powder characteristics on the SLM samples [10], and the particle size distribution are generally ignored. Especially, the supply of high quality metal powder has become an obstacle for SLM development.

The product quality of selective laser melting (SLM) is closely related to the alloy powder size distribution. The small voidage of alloy powder bed, mixed with the coarse and fine-sized powder, is beneficial to improve the density of SLM product. While, the fine-sized alloy powder would result in the poor powder spreading uniformity in the SLM equipment, which leads to the formation of holes in the SLM product. Therefore, in this work, the 316L stainless steel powder was prepared by a vacuum atomization furnace and sieved into a coarse-sized distribution and a fine-sized distribution. The effect of particle size distribution of 316L stainless steel powder on SLM process was investigated.

2. Experimental Procedure

In order to investigate the effect of particle size distribution on the SLM process, the 316L stainless steel powder, as shown in figure 1, was prepared by a vacuum atomization furnace and sieved into a coarse-sized distribution range from 15 to 53 μm with a median diameter of 39.1 μm, and a fine-sized distribution range from 10 to 38 μm with a median diameter of 15.5 μm. The chemical composition of 316L stainless steel powder was listed in Table 1. According to the Horsfield filling theory, as shown in Figure 2, the quantity ratio of powder with fine-sized to coarse-sized is 1:1, the diameter ratio is 0.414:1, and the mass ratio is 0.071:1, in the face-centered cubic stacking model. Thus, the above two powders of different particle sizes basically meted the diameter ratio requirement of Horsfield filling theory. Therefore, in this study, the powders of coarse-sized and fine-sized were mixed in a quantity ratio of 1:1. In addition, the quantity ratio of powder with fine-sized to coarse-sized was further adjusted to 2:1 and 3:1. Their physical properties, including the bulk density, the hall flow rate, the angle of repose, were summarized in Table 2. In addition, the powder size distributions were described in Figure 3. It can be seen that the powder size gradually shows a bimodal distribution, with the increasing proportion of fine-sized powder.

![Figure 1](image1.jpg)

**Figure 1.** SEM morphology (×200) of 316L stainless steel powder

![Figure 2](image2.png)

**Figure 2** Model of Horsfield filling theory
Table 1 Chemical composition of 316L stainless steel powder (mass fraction, %)

|   | Fe    | Ni    | Cr  | Mo  | Mn  | Si  | C       | O       |
|---|-------|-------|-----|-----|-----|-----|---------|---------|
|   | Bal.  | 11.26 | 18.34 | 2.08 | 1.30 | 0.52 | 0.0300  | 0.0291 |

Table 2 Physical properties of 316L stainless steel powder

| No. | Quantity ratio of powder with fine-sized to coarse-sized | Bulk density (g/cm³) | Hall flow rate (g/50s) | Angle of repose (°) |
|-----|---------------------------------------------------------|----------------------|------------------------|---------------------|
| 1#  | 0:1                                                     | 4.38                 | 13.53                  | 29.5                |
| 2#  | 1:1                                                     | 4.40                 | 15.79                  | 30.0                |
| 3#  | 2:1                                                     | 4.47                 | 21.70                  | 31.4                |
| 4#  | 3:1                                                     | 4.53                 | 29.03                  | 32.0                |

Figure 3. Powder size distributions

The SLM process parameters of 316L stainless steel powder were summarized in Table 3. The size of SLM samples was 6×6×6 mm³. And then, the transversal and lengthwise surface, etched with nitromurlatic acid, were observed in SEM. In addition, the density of samples were measured using Archimedes drainage method. The mechanical properties of sample were measured with a creep fatigue testing machine.

Table 3 SLM process parameters

| Parameter | Scanning speed | Laser power | Thickness of powder bed |
|-----------|----------------|-------------|-------------------------|
| Value     | 2000 mm/s      | 350 W       | 20 μm                   |

3. Results and Discussion

3.1. Microstructure of SLM sample
The horizontal and vertical surface morphology of SLM sample are shown in figure 4.
Figure 4. Surface morphology of SLM sample: (a) Vertical surface of powder 1#; (b) Horizontal surface of powder 1#; (c) Vertical surface of powder 2#; (d) Horizontal surface of powder 2#; (e) Vertical surface of powder 3#; (f) Horizontal surface of powder 3#; (g) Vertical surface of powder 4#; (h) Horizontal surface of powder 4#

Generally speaking, as the amount of fine-sized powder increases, the number and size of cracks in the surface of SLM sample increase significantly. For the powder 1#, the melting channels in the vertical surface are evenly arranged in a fish scale without obvious defects, the horizontal surface also has no significant defects. When a small amount of fine-sized powder is added (powder 2#), although the melt channel distribution is uniform, some cracks (A and B) could be found in the vertical and horizontal surface. In the case of powder 3#, the larger cracks (C and E) and holes (D) are formed at the junction of the melt channel. Furthermore, for the SLM sample produced by the powder 4#, the melt channel in the vertical surface is chaotic, a large number of small holes (F) appear inside the melt channel, and many pores (G) exits at the junction of orthometric metal channel. In addition, a large amount of spheroidized particles appears in the melt channel breakage (H) of the horizontal surface. The main reason for holes and cracks could be concluded that the fine-sized powder, with the large specific surface, is easy to bond with the coarse-sized powder, which leads to the decreasing of powder fluidity.
3.2. Macro performance of SLM sample
The relative density of the SLM samples produced by 316L stainless steel powder with different powder size distributions are summarized in figure 5. Generally speaking, as the amount of fine-sized powder increases, the relative density of SLM sample gradually decreases from 96.2% to 90.8%. As mentioned above, the larger amount of fine-sized powder results in a greater number of holes in the SLM samples, which reduces the relative density of SLM sample.

![Figure 5. Relative density of SLM sample](image)

The comparisons of mechanical properties at room temperature, including tensile strength, yield strength and elongation, are summarized in figure 6. It can be seen that the tensile strength, yield strength and elongation of SLM sample prepared by the 316L stainless steel powder without the addition of fine-sized powder are higher than those with the addition of fine-sized powder. It is noted that the tensile strength and yield strength of SLM samples decrease, while the elongation of SLM samples increase, with the increasing amount of fine-sized powder. The main reason for this phenomenon is that the occurrence of cracks causes the residual stress to be released, which increases the elongation of SLM samples, after adding a large amount of fine powder.

![Figure 6. Mechanical properties at room temperature](image)

4. Conclusions
1) Due to the large specific surface of the fine-sized powder, it is easy to bond with the coarse-sized powder. It reduces the fluidity of powder, resulting in the pores and cracks during the SLM layering process. Therefore, as the amount of fine-sized powder increases, the density and strength of the SLM sample gradually decrease.

2) The addition of fine-sized powder to the coarse-sized powder results in a decrease in the elongation of SLM sample. However, with the increase of the addition amount of the fine-sized powder, the residual stress is released due to the formation of a large number of cracks and pores, so that the elongation of SLM sample is slightly increases.
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