The influence of process parameters on the performance of nylon 6 selective laser sintering parts

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Abstract: During the selective laser sintering process, the sintering behavior between powders is mainly affected by thermal effect. There are a large number of process parameters influencing the variation of temperature and molten pool, of which the laser density and scanning speed play a crucial role in determining the performance of the parts. In this paper, the effects of laser density and scanning speed on the precision and strength of polyamide 6 selective laser sintering parts were systematically investigated. The results show that with the increase of energy density, the positive dimensional deviation of the parts in three directions increases gradually, and the tensile strength increases at beginning and then decreases. When the laser power and scanning speed were changed, the tensile strength of the parts varied between 5.62 MPa and 58.74 MPa.

1. Introduction

Polyamide 6 (PA6) is a kind of high-performance polymer material with a strength of up to 160 MPa, which is 2 to 3 times better than the general engineering plastics. It has excellent thermal stability and can maintain high physical properties at a high temperature up to 130 °C [1]. Due to its excellent thermal and mechanical properties, PA6 is widely used in mechanical, electronics, transportation, and other industrial filed. Additive manufacturing technology (3D printing) is a rapid prototyping technology without mold, which is based on digital model files through printing layer by layer. The selection of materials for selective laser sintering (SLS) has a wide range, in theory, any material which can be sintered by laser.

Previous studies showed that more than 130 factors can affect the performance of additive manufacturing parts, which can be divided into four categories: material properties, processing environment, equipment, and process parameters. Considering that the first three factors were determined before manufacturing, hence the process parameters are the key factors that determine the performance of the parts [2-4]. At present, due to the high cost and complicated processing conditions of PA6 for SLS forming, few researches were done on the PA6 forming process parameters optimization, the mechanism between process parameters and part performance is still unclear. Therefore, it is necessary to illustrate the fundamental mechanism of process parameters on the parts performance, optimization process parameters, and further provides guidance for subsequent production. This paper aims to systematically study the variation of precision and mechanical properties of PA6 SLS parts under different laser power and scanning speeds.
2. Materials and experimental methods

2.1. Materials and forming equipment

2.1.1. Material. In this study, a mixed powder, which consists of 60 wt.% of PA6 and 40 wt.% of glass beads (hereinafter referred to as PA6), was used for sintering experiments (SINTERLINE XP 1537/A, Solvay SA Group). The scanning electron microscope (Sirion 200, FEI, Holland) image of PA6 powder shows a smooth surface close to a spherical shape, meaning that it has good flowability during the recoating process. The average particle size of the powder is 25.6 μm, and the range is from 12.3 μm to 50.7 μm, which is considered to be a suitable particle size for the SLS process. Hence, the powder can be directly employed for sintering experiments.

2.1.2. Forming equipment. A laser powder bed fusion equipment (HK P500 SLS) was employed to perform the powder-sintering experiments. The equipment is equipped with a CO2 laser device, which has a radius of 0.35 mm, a maximum power of 55 W, and a maximum scanning speed of 5000 mms⁻¹. The preheating temperature of the device can reach 200 °C during printing. The equipment is equipped with HUST 3DP control software independently developed by Huazhong University of Science and Technology, which can directly read the STL files of the model.

2.2. Experimental design and testing

2.2.1. Experimental design. To better verify the thermal behavior under different laser power and scanning speed, the concept of energy density is introduced:

\[ E_D = \frac{P}{v \times L} \]  

Here, \( E_D, P, v, L \) represent energy density, laser power, scanning speed and scanning distance respectively. By changing the laser power and scanning speed, 13 sets of experiments as shown in Table 1 were conducted. The energy density varies from 9.52e-3 Jmm⁻² to 1.43e-1 Jmm⁻².

| Number | Laser power (W) | Scanning speed (mms⁻¹) | Energy density (Jmm⁻²) |
|--------|-----------------|------------------------|-----------------------|
| 1      | 30              | 5000                   | 1.71e-2               |
| 2      | 30              | 4000                   | 2.14e-2               |
| 3      | 30              | 3000                   | 2.86e-2               |
| 4      | 30              | 2000                   | 4.29e-2               |
| 5      | 30              | 1000                   | 8.57e-2               |
| 6      | 50              | 3000                   | 4.76e-2               |
| 7      | 40              | 3000                   | 3.81e-2               |
| 8      | 20              | 3000                   | 1.90e-2               |
| 9      | 10              | 3000                   | 9.52e-3               |
| 10     | 10              | 1000                   | 2.86e-2               |
| 11     | 20              | 1000                   | 5.71e-2               |
| 12     | 40              | 1000                   | 1.14e-1               |
| 13     | 50              | 1000                   | 1.43e-1               |
2.2.2. **Characterization and testing.** A vernier caliper with an accuracy of 0.01 mm was employed to measure the three-dimensional size of the parts. A universal testing machine (AG-IC100KN, SHIMADZU Corporation, Japan) was employed for testing the mechanical properties.

### 3. Results and discussion

#### 3.1. Fabrication accuracy

Owing to slicing and equipment errors during the selective laser sintering process, the phenomenon of "secondary sintering" and "Z-axis surplus" occurs frequently in the forming process, which causes the size of the printed parts is often larger than the original size in the digital model. The specimens with a size of 50 mm×10 mm×2 mm were fabricated under the first 9 groups of parameters in Table 1. Figure 1 shows the relative average errors in the three directions of specimens. The result shows that increasing the energy density leads to a larger positive deviation of the parts in the $x$, $y$, and $z$ directions, and the error bar also increases.

![Figure 1. Relative dimension deviations of (a) $x$ direction (b) $y$ direction (c) $z$ direction under different energy density.](image)

When the energy density increases from 9.52e-3 Jmm$^{-2}$ to 8.57e-2 Jmm$^{-2}$, the dimension deviation in the $x$-direction increases from 0.87 mm to 1.58 mm, the dimension deviation in the $y$-direction increases nearly 4 times (from 0.54 mm to 2.02 mm), and the dimension deviation in the $z$-direction increases from 0.08 mm to 1.28 mm. It indicates that energy density has a great effect on parts size accuracy, the dimension deviation increases to a large extent.

It can be attributed to the fact that a larger energy density means a bigger heat input, which leads to a surplus effect during the laser sintering process, causing more powder bonding and forming. The bonding and forming behavior are mainly decided by the laser diameter and energy penetration in the depth direction.

#### 3.2. Mechanical properties

In present study, 13 sets of parameters in Table 1 are selected, and each set of parameters is printed with three samples.

As shown in figure 2, the tensile strength of the parts varies between 5.62 MPa and 58.74 MPa under different process parameters. Besides, when the energy density is 9.5e-3 Jmm$^{-2}$ ($P=10$ W, $v=3000$ mms$^{-1}$), the tensile strength reaches the lowest value, ~5.62 MPa. As the energy density increases, the tensile strength of the part gradually increases. When the energy density increases to 5.71e-2 Jmm$^{-2}$ ($P=20$ W, $v=1000$ mms$^{-1}$), the mechanical properties of the parts achieve the highest value, ~58.74 MPa. Then as the energy density continues to increase, the tensile strength decreases.
Figure 2. Relationship between energy density and tensile strength.

The above phenomenon is mainly caused by the fact that when the laser density is small, the heat input is insufficient, and the PA6 powder cannot be melted completely. In addition, the fluidity of the powder is not enough, and the particles cannot be well bonded and formed. Increasing the energy input, the heated area of the powder increases conspicuously, the three-dimensional size of the molten pool and the flow rate increase together, hence the density of parts are improved. However, when the energy density exceeds a reasonable value, the material will decompose due to the excessive energy input, which will degrade the mechanical property of the part.

4. Conclusions
This paper systematically studies the effect of energy density on the precision and mechanical properties of the SLS PA6 parts. The conclusions are as follow:

- As the energy density increases, the positive dimension deviations of the parts in three directions gradually increase. The positive dimension deviations in the $x$-direction range from 0.87 mm to 1.58 mm, the $y$-direction ranges from 0.54 mm to 2.02 mm and the $z$-direction ranges from 0.08 mm to 1.28 mm.
- With the change of energy density, the tensile strength of parts varies between 5.62 MPa and 58.74 MPa. Appropriately increasing heat input can enhance mechanism property, and the excessive heat input is harmful for improving the tensile strength of parts.

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