1. Introduction
The existing method for measuring the density of the powder bed of the selective laser sintering powder layer is mainly to extract a certain volume of the powder layer powder, weigh the powder quality of the extracted powder layer, and use the mass formula to calculate the overall density of the powder layer[1]. The main disadvantage of this method is that it is extremely difficult to extract a certain volume of powder layer powder. During the extraction process, the extraction tool and powder effect change the volume of the powder layer. It is difficult to ensure the volume and unextracted powder of the powder layer consistent before.

Therefore, there is a need for a more reliable and accurate method for measuring the powder density of the powder layer. This paper proposes a powder density measurement method based on the plumb method, which can carry out the powder bed density measurement without causing major damage to the powder bed. Firstly, a series of density powder beds are prefabricated in the powder box, and the device is used for density calibration. The steel balls are freely dropped into the powder bed, and the density of the powder bed is measured by the depth of the steel balls falling into the powder bed. After the calibration is completed, the density is determined. The mathematical relationship between the density of the powder bed and the depth of the steel ball falling into the powder bed can be fitted[2-3].

When the measurement of the density of the powder bed is required, the steel ball is dropped into the powder bed from the same height as the calibration, and then the depth of the steel ball falling into the powder bed is measured, and the depth is brought into the above mathematical relationship to
calculate the powder bed density. The method is convenient and quick, and can improve the efficiency and precision of the powder bed density measurement.

2. Powder bulk density and tap density measurement

According to the previous literature research, it can be known that the powder bed of the selective laser sintering equipment has a powder bed density that is not less than the bulk density of the powder and is not greater than the tap density of the powder. Since it is necessary to artificially produce a series of powder beds of different densities in the calibration of the density of the powder bed, it is necessary to measure the bulk density and the tap density of the test powder before the calibration, and the artificially produced powder bed density interval is loose density to tap density[4].

The measuring equipment used in this paper is BT-1000 powder comprehensive characteristic tester, electronic scale and constant volume container, as shown in figure 1.

![Figure 1. Measuring equipment](image1)

2.1. Measurement of bulk density

The bulk density refers to the powder under the specified conditions and naturally filled with a specific container state, that is, the mass per unit volume when the powder is loosely packed, often expressed in g/cm³, which is a process property of the powder. The bulk density is measured by the vibrating funnel method, that is, the powder is placed in a funnel with a vibrating device, and vibrated under certain conditions, and the powder is freely dropped from the funnel hole by a certain height by means of vibration, and filled with a container filled with a constant volume of 100 ml.

Continuous measurement 5 times and weigh the 100ml container and the mass of the loaded powder, expressed in G, as shown in figure 2. And record these five measurements in Table 1. The mass of the 100ml container G₀ is 410g, as shown in figure 1.

| Times/x | 1  | 2  | 3  | 4  | 5  |
|---------|----|----|----|----|----|
| Mass Gᵢ/g | 456.8 | 456.9 | 457.7 | 456.6 | 456.4 |

After 5 measurements, the average mass of the filled powder container was taken:

\[
G = \frac{G₁ + G₂ + G₃ + G₄ + G₅}{5} = 456.88g
\]  

![Figure 2. Measurement of bulk density](image2)
The calculated bulk density is:
\[ \rho_b = \frac{G - G_0}{100} = \frac{456.88 - 410}{100} = 0.468 \text{g/cm}^3 \]  
(2)

2.2. Measurement of tap density

The tap density refers to the mass per unit volume measured after the powder is vibrated in a specific container under specified conditions, the specified conditions is that the stroke is 3mm and vibration frequency is 100 times/min - 300 times/min \cite{5}. That is, the mass per unit volume of the powder compaction filling, often expressed in g/cm$^3$, is a process property of the powder. There are two methods for measuring the tap density of a powder: a fixed mass method and a fixed volume method. This measurement uses a fixed volume method, that is, the powder after tapping is filled with a fixed volume container, as shown in figure 3.

![Image](image1.png)

Figure 3. Measurement of tap density

Continuous measurement 5 times and weigh the 100ml container and the mass of the loaded powder, expressed in Gx’, as shown in figure 3. And record these five measurements in Table 2.

| Times/x | 1   | 2   | 3   | 4   | 5   |
|---------|-----|-----|-----|-----|-----|
| Mass Gx’/g | 474.9 | 474.4 | 474.4 | 474.4 | 474.4 |

After 5 measurements, take the average of the mass after full shaking:
\[ G = \frac{G_1 + G_2 + G_3 + G_4 + G_5}{5} = 474.5 \text{g} \]  
(3)

The calculated tap density is:
\[ \rho_t = \frac{G - G_0}{100} = \frac{474.5 - 410}{100} = 0.645 \text{g/cm}^3 \]  
(4)

After the above measurement, the selective laser sintering of the ABS powder printed in this test has a bulk density of 0.468 g/cm$^3$ and a tap density of 0.645 g/cm$^3$, which is a prefabrication for subsequent selective laser sintering of different density powder beds. Provide a density interval reference range.

3. Powder bed density calibration and measurement principle based on plumb method
Figure 4. Description of measurement principle

As shown in Figure 4, the prefabricated powder bed in the figure 4 is a powder bed which has been prefabricated by a pre-preparation. The steel ball shown in Figure 4(a) is released from the height H, and falls into the pre-powder bed as shown in Figure 4(b), the diameter of the steel ball is counted as “d”. The distance to the prefabricated powder bed was measured using a laser range finder, calculated as “h₁”, the distance to the highest point of the steel ball, calculated as “h₂”. Then the steel ball falls into the depth of the powder bed, which is counted as h:

\[ h = d - (h_1 - h_2) \]  

(5)

By prefabricating a series of powder beds of different densities, the principle is used to measure the depth h of the steel balls falling into different density powder beds, and the density of the powder bed is measured by the depth “h” of the steel balls falling into the powder bed to achieve the purpose of calibrating the powder beds of different densities. After the calibration is completed, the relationship between the density of the powder bed and the depth of the steel ball falling into the powder bed and the mathematical relationship can be fitted.

When the measurement of the density of the powder bed is required, the steel ball is dropped into the powder bed from the same height as the calibration, and then the depth of the steel ball falling into the powder bed is measured, and the depth is brought into the mathematical relationship described above to calculate the density of the powder bed.

4. Test bench design and data measurement

4.1 The structure of the test bench and its key components

As shown in Figure 5, the overall structure of the test bench is mainly composed of a frame, a steel ball release device, a powder box, a powder box pedestal, a slide rail, a rotating shaft, a laser range finder and a laser range finder mounting bracket. The powder box is placed on the powder box pedestal, and the powder box pedestal is connected to the slider on the slide rail by bolts. The laser range finder is mounted on the Laser range finder mounting bracket that can be rotated about the rotating shaft.

The steel ball release device is composed of a bracket and a steering gear, and the steering gear has two working positions as shown in figure 6. In the A position, the steering gear prevents the steel ball from falling, and this state is also the normal state of the steering gear. When the release switch is pressed, the steering gear quickly moves to the B position, and the steel ball falls at the same time and falls into the powder bed.

In order to achieve high-precision distance measurement[6-8], the high-precision distance measuring sensor selected for this test bench is the LDS-S-20 standard laser displacement sensor. The measuring range is 20mm; the measuring accuracy is 1μm.
4.2 Data measurement
First, the powder bed of the bulk density and the tap density was prefabricated using the powder box in the Figure5, and the container had a net weight of 50 g and a volume of 198 cm$^3$. The density of the pre-formed powder bed can be obtained by subtracting the net weight of the powder box divided by the volume of the powder box. Calculated as follows:

$$\rho = \frac{M - m}{V}, \text{ g/cm}^3$$

In the above formula:The M is the weight of the powder box after tapping;the m is the net weight of the powder box;the V is volume of the powder box.

The powder box in which the powder bed was previously prepared was placed on a test stand, and the distance $h_1$ of the surface of the powder bed was measured using a laser distance measuring sensor[8]. Then adjust the position of the powder box and make the two steel balls fall into the powder bed respectively, and measure the distances $h_2'$ and $h_2''$ of the highest points of the two steel balls respectively, and take the average value as $h_2$ [9], shown in figure 7.
Table 3. Test data

| NO. | Powder bed density $\rho/(g/cm^3)$ | Falling depth of steel ball $h/mm$ | Depth value $l/mm$ |
|-----|-----------------------------------|-----------------------------------|-------------------|
| 1   | 0.498                             | -1.405                            | 13.405            |
| 2   | 0.508                             | -0.866                            | 12.866            |
| 3   | 0.572                             | 6.862                             | 5.138             |
| 4   | 0.577                             | 7.658                             | 4.342             |
| 5   | 0.589                             | 8.305                             | 3.695             |
| 6   | 0.600                             | 8.775                             | 3.225             |
| 7   | 0.610                             | 9.280                             | 2.720             |
| 8   | 0.623                             | 9.385                             | 2.615             |
| 9   | 0.637                             | 9.682                             | 2.318             |

5. Conclusions
Through the above test methods and data measurement methods and then our completing the prefabrication of nine species of powder beds of different densities and their related data measurements, the measured or calculated data are recorded in Table 3. The pre-fabricated bed density $\rho$ and the steel ball falling into the powder bed depth $h$ are introduced into the Matlab software to produce a curve of $\rho$ and $h$, as shown in Figure 8. The curve fitting method is Power2, and the mathematical expression is a power function with a constant term. The mathematical expression is $\rho=0.1047h^{0.705}-0.4752$. These test data and methods provide data support for the subsequent measurement of the density of a series of powder beds.

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