Effect of SLM Process Parameters on Relative Density of Maraging Steel (18Ni-300) Formed Parts

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Abstract. Taking maraging steel (18Ni300) powder as the research object, the influence of the density of forming parts such as laser power p, scanning speed v, scanning spacing s and powder thickness h during the rapid forming process of SLM laser was studied by orthogonal test. The experimental results show that the laser power and scanning spacing have a significant effect on the density of the molded part, while the powder thickness and scanning speed have no significant effect on the relative density of the molded part. The order of importance of the influence of each factor on the compactness of the formed part is the laser power, the scanning spacing, the scanning speed, and the powder thickness. The best combination of process parameters is a laser power of 260 W, a scanning speed of 700 mm/s, a scanning spacing of 0.11 mm, and a powder thickness of 0.02 mm. When the laser volume energy density is between 70 J/mm$^3$ and 185 J/mm$^3$, the relative density can reach more than 99%, and it can increase to 99.99% during this interval.

Keywords. Maraging steel (18Ni-300), relative density, selective laser melting, orthogonal experiment.

1. Introduction
Selective Laser Melting (SLM) forming technology is to use a high-energy beam laser to selectively select powder materials to melt and solidify them. Using the “discrete-stack” principle, three-dimensional solids are constructed by printing layer by layer [1-2].

Maraging Steel(18Ni-300) is a commonly used mold steel, which has a high absorption rate of laser beam, which is suitable for the forming characteristics of SLM. However, SLM forming is performed under the scanning of a high-speed laser beam, and instantaneous melting, solidification, and cooling forming occur, so it is difficult to avoid voids inside the formed part. Thereby reducing the compactness and mechanical properties of the formed part [3-5].

Raus et al. [6] Print AlSi10Mg parts using selective laser melting. By changing process parameters and remelting methods, the final density reached 99.8%. Wang, et al. [7] AlSi10Mg alloy parts were printed using selective laser melting technology. It was concluded that all SLM products have high density (relative density > 97%) and excellent mechanical properties. Tucho et al. [8] Print 316L stainless steel parts with selective laser melting. The trend between energy density and density and hardness was studied, and it was proved that energy density has the largest effect. Zhang et al. [9]. Ag/SnO2 composites were printed. The effects of different energies on Ag/SnO2 composites were studied. The results show that the relative density and hardness of Ag/SnO2 composites are affected by energy density. Ag/SnO2 composites have a uniform microstructure and high relative strength. Souza et al. [10] A part of maraging steel 300 was prepared by selective laser melting technology. The effects of
process parameters on densification and performance were studied, and it was shown that porosity and hardness are strongly related to processing parameters. Rashid et al. [11] studied the effect of two different scanning strategies on the scanning results. The relative density of the samples printed by the dual scan method was found to be relatively high.

In this test, the SLM forming of maraging steel (18Ni-300) was studied. Orthogonal experimental analysis using variance. The effects of laser power, scanning speed, scanning interval and powder thickness on the density of formed parts were investigated. At the same time, the process of laser melting and forming Maraging Steel(18Ni-300) was optimized.

2. Test Equipment and Materials

2.1. Test Equipment
The test equipment is a metal printer model SLM 125 HL manufactured by the German company SLM solutions as shown in figure 1. The Measuring equipment is a Mettler ME204E electronic analytical balance with an accuracy of 0.0001 g.

![Figure 1. SLM125HL.](image)

2.2. Test Materials
The test material is Maraging Steel (18Ni-300) powder (18Ni-300) (figure 2). The particle size of the powder is 10-45 μm (figure 3). The material element content is shown in table 1.

| Element | Ni  | Co  | Mo  | Ti  | Al  | Mn  | Si  | P   | S   | C   | Fe  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Content (%)| 18-19 | 8.5-9.5 | 4.7-5.2 | 0.5-0.8 | 0.05-0.15 | 0-0.10 | 0-0.1 | 0-0.01 | 0-0.01 | 0-0.03 | Bal. |

![Table 1. Element content.](image)

![Figure 2. Micro morphology of the maraging steel (18Ni300) powder.](image)

![Figure 3. Particle size distribution of the maraging steel (18Ni300) powder.](image)
2.3. Measurement of Relative Density
This test uses the drainage method to measure the relative density. The density formula is as follows:

\[ m = \rho \times V \]  
(1)

First measure the mass \( m_1 \) of the molded part. Then pour an appropriate amount of water into the beaker, and then hang the shaped part in the water to ensure that the water depth can be immersed in the test piece. Record the reading of the balance as \( m_2 \). According to equation (1):

\[ V_{m_1} = \frac{m_2}{\rho_{H_2O}} \]  
(2)

According to equations (1) and (2), we can get

\[ \rho_{m_1} = \frac{m_1 \times \rho_{H_2O}}{m_2} \]  
(3)

Then the relative density of the formed part is

\[ \rho_{rel} = \frac{\rho_{m_1}}{\rho} \times 100\% \]  
(4)

In the formula, \( \rho_{rel} \) is the relative density; \( \rho_{m_1} \) is the density of maraging steel (18Ni-300) formed by SLM; \( \rho \) is the density of maraging steel (18Ni300) 18Ni-300 \( (\rho = 7.85 g/cm^3) \).

\( \rho_{H_2O} \) is the density of the water. The SLM formed part used in this test was a 10 mm × 10 mm × 10 mm cube formed part as shown in figure 4.

![Figure 4](image)

**Figure 4.** Samples of forming parts.

2.4. Relationship between Energy Input and Relative Density of Formed Parts during Forming
When the powder is melted, when a large energy input is received per unit volume, a large shrinkage deformation, or even vaporization may occur. Too little energy input per unit volume may result in incomplete powder melting. These defects directly affect the relative density of the formed part.

\[ \psi = \frac{P}{vhs} \]  
(5)

where \( \psi \) is the laser volume energy density, \( P \) is the laser power, \( v \) is the scanning speed, \( h \) is the powder thickness, \( s \) is the scanning spacing.

According to equation (5), laser power, scanning speed, scanning interval, and powder thickness are all factors that affect the laser volume energy density. Therefore, Therefore, this article mainly studies the influence of these four Process Parameters on the relative density of molded parts.
3. Orthogonal Experiment Design

3.1. Factor Level Table Design
This experiment uses four-factor and four-level orthogonal tests. The test factors are established as four Process Parameters, such as laser power (p), scanning speed (v), powder thickness (h), and scanning spacing (s) as shown in table 2.

| Level | Laser power (W) | Scanning speed (mm·s⁻¹) | Powder thickness (mm) | Scanning spacing (mm) |
|-------|-----------------|--------------------------|-----------------------|------------------------|
| 1     | 180             | 500                      | 0.02                  | 0.08                   |
| 2     | 220             | 700                      | 0.035                 | 0.11                   |
| 3     | 260             | 900                      | 0.05                  | 0.14                   |
| 4     | 300             | 1100                     | 0.065                 | 0.17                   |

3.2. Orthogonal Test Results and Analysis
Table 3 shows the relative density test results of 16 samples obtained through the test. Table 4 is the calculation result of range analysis, and Table 5 is the analysis table of variance.

From the range values in table 4, the order of importance of the four influencing factors is laser power, scanning spacing, scanning speed, and powder thickness. From the value of k in table 4, the best combination of process parameters can be obtained: the laser power is 260 W, the scanning spacing is 0.11 mm, the scanning speed is 700 mm/s, and the powder thickness is 0.02 mm. Based on this group of process parameters to carry out verification experiments, the density of the formed part was 99.99%, which was larger than that of the 16 groups of orthogonal experiments.

From table 5, the laser power and scanning spacing have a significant effect on their relative density of the formed part. The scanning speed and powder thickness have no significant effect on the density of the formed part.

| Serial number | Laser power (W) | Scanning speed (mm·s⁻¹) | Scanning spacing (mm) | Powder thickness (mm) | Relative density (%) |
|---------------|-----------------|--------------------------|-----------------------|------------------------|----------------------|
| 1             | 180             | 500                      | 0.08                  | 0.02                   | 96.68                |
| 2             | 180             | 700                      | 0.11                  | 0.035                  | 97.5                 |
| 3             | 180             | 900                      | 0.14                  | 0.05                   | 93.35                |
| 4             | 180             | 1100                     | 0.17                  | 0.065                  | 90.24                |
| 5             | 220             | 500                      | 0.11                  | 0.05                   | 99.79                |
| 6             | 220             | 700                      | 0.08                  | 0.065                  | 98.99                |
| 7             | 220             | 900                      | 0.17                  | 0.02                   | 97.57                |
| 8             | 220             | 1100                     | 0.14                  | 0.035                  | 95.41                |
| 9             | 260             | 500                      | 0.14                  | 0.065                  | 98.01                |
| 10            | 260             | 700                      | 0.17                  | 0.05                   | 98.01                |
| 11            | 260             | 900                      | 0.08                  | 0.035                  | 99.98                |
| 12            | 260             | 1100                     | 0.11                  | 0.02                   | 99.79                |
| 13            | 300             | 500                      | 0.17                  | 0.035                  | 98.22                |
| 14            | 300             | 700                      | 0.14                  | 0.02                   | 99.02                |
| 15            | 300             | 900                      | 0.11                  | 0.065                  | 98.07                |
| 16            | 300             | 1100                     | 0.08                  | 0.05                   | 99.99                |
Table 4. Calculation results of range.

| Level | Laser power | Scanning speed | Scanning spacing | Powder thickness |
|-------|-------------|----------------|------------------|-----------------|
| k₁    | 94.4425     | 98.1750        | 98.6850          | 98.2650         |
| k₂    | 97.9400     | 98.3800        | 98.7875          | 97.7775         |
| k₃    | 98.9475     | 97.2425        | 96.4475          | 97.5600         |
| k₄    | 98.6000     | 96.1325        | 96.0100          | 96.3275         |
| range | 4.505       | 2.2475         | 2.7775           | 1.9375          |
| Sorting | 1         | 3              | 2                | 4               |

Table 5. Analysis of variance.

| Test factor      | SS      | df | MS    | F      | Saliency |
|------------------|---------|----|-------|--------|----------|
| Laser power      | 51.4131 | 3  | 17.1377 | 22.6398 | *        |
| Scanning speed   | 12.6559 | 3  | 4.2186 | 5.5730 |          |
| Scanning spacing | 25.5781 | 3  | 8.5260 | 11.2633 | *        |
| Powder Thickness | 8.1634  | 3  | 2.7211 | 3.5947 |          |
| Error            | 2.2709  | 3  | 0.7570 |        |          |
| Total            | 394.4350| 15 |       |        |          |

4. Analysis of Forming Process Parameters Affecting the Relative Density of Formed Parts

4.1. The Relationship between Laser Power and Relative Density of Formed Parts
As shown in figure 5, the laser power was increased from 180 W to 300 W. The relative density of the molded article increases first and then decreases. The laser power is 180 W to 260 W. The relative density of the shaped parts increases. The laser power increases, the energy received by the powder becomes more abundant. And the higher the powder's fluidity after melting, the less internal pores remain and the higher the relative density during re-solidification. The laser power is 260 W to 300 W, the relative density of the formed part tends to decrease. When the laser power is too high, the powder receives too much energy, which will cause the powder to overburn and cause vaporization, which will cause holes to appear inside during molding, resulting in a reduction in density.

4.2. The Relationship between Scanning Speed and Relative Density of Formed Parts
As shown in figure 5, when the scanning speed is from 500 mm/s to 1100 mm/s, the relative density of the formed article first increases and then decreases. The slower the speed in the laser scanning process, the longer the laser stays on the powder, the greater the energy the powder gets, and the more the powder melts more fully. Therefore, the porosity of the formed part is low at a low scanning speed, and the relative density is large. However, when the scanning speed is too low and the laser stays in the powder for too long, the energy absorbed by the powder will be too large, which will cause the powder to vaporize and form pores, which will reduce the relative density.

4.3. The Relationship between Scanning Spacing and Relative Density of Formed Parts
As shown in figure 5 that when the scanning spacing is 0.08 mm-0.17 mm, the relative density of the formed part increases first and then decreases. When the scanning spacing is small, each layer is flat due to the overlap of the melt channels, but as the scanning spacing increases, each layer starts to be uneven due to too few overlaps. The overlap rate decreases significantly with the increase of the scanning spacing. When the overlap rate is too small or cannot be overlapped, a large size gap exists between adjacent melt channels in the same forming layer. This situation will increase the internal porosity of the part and reduce the relative density of the part when forming the solid. However, when there are too many overlaps in the melt channel [12], the repeated energy reception of the powder in the overlap area
will cause the powder to splash and thus reduce the compactness of the formed part.

![Graphs showing the relationship between process parameters and relative density.](image)

**Figure 5.** Relationship between the process parameters of selective laser melting and the relative density of formed parts.

### 4.4. The Relationship Between the Thickness of Powder Coating and The Density of the Formed Part

As shown in figure 5 that the relative density decreases when the powder thickness is from 0.02 mm to 0.065 mm. When the thickness of the powder is low, the thickness of the laser-melted powder is small. On the one hand, the powder can be completely melted. On the other hand, the upper half of the previous forming layer can be remelted again to make it flatter. The forming surface of each layer is relatively flat. With the increase of the thickness powder, the energy required to completely melt the powder increases. When the energy cannot maintain the complete melting of the powder, it will lead to the formation of voids in the formed part. Therefore, the thickness powder during molding will have a greater impact on the porosity of the molding. The higher the porosity, the lower the density.

### 4.5. Relationship between laser volume energy density and Relative Density of Formed Parts

As shown in figure 6 that the relative density increases gradually when the laser volume energy density increases within a certain range. When the laser volume energy density is between 75 J/mm$^3$ and 185 J/mm$^3$, the density can reach more than 99% and can increase to 99.99% in this interval, but it starts to decrease again. But more than 185 J/mm$^3$ began to decrease again. It can be seen that too much or too little laser volume energy density will be the deterioration of the relative density of the formed part. This is because the powder cannot be fully melted when the laser volume energy density is low, and the liquid phase also easily shrinks into spheres, which weakens the wettability of the liquid phase and eventually causes a single crack. Increasing the laser volume energy density increases the amount of molten metal powder, reduces the surface tension and viscosity of the molten pool, and makes the liquid phase infiltration better [13]. It also fills the grooves and pits on the previous layer. In order to make the relative density of the molded parts higher.
5. Conclusion

Based on orthogonal experiments and analysis of variance. The relationship between the selected laser melting forming process parameters and the relative density of the formed parts was studied. Through the above research and analysis. conclusions as follows:

(1) Maraging Steel (18Ni-300) powder is formed by SLM. The optimal process parameter combination is 260 W laser power, 700 mm/s scan speed, 0.11 mm scan pitch, and 0.02 mm powder thickness. The verification test shows that the relative density of the formed part can reach 99.99%, which is higher than the above test results.

(2) The important order of the influence of molding process parameters on the molded part is laser power > scanning distance > scanning speed > powder thickness. Both laser power and scanning distance are important factors.

(3) The laser volume energy density is 75 J/mm$^3$-185 J/mm$^3$, the relative density can reach 99%, and the highest density can reach 99.99%. When the laser volume energy density is lower than 75 J/mm$^3$ or higher than 185 J/mm$^3$, the relative density decreases.

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