Influence of laser power and scan speed on the microstructure and properties of GH4169 alloy prepared by selective laser melting

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Abstract: In this work, GH4169 alloy prepared by selective laser melting (SLM) used the domestic SLM equipment, the effects of different laser power and scan speed on the density, microstructure and mechanical properties of GH4169 alloy were systematically studied. The results showed that the density and hardness of SLM products increased with the increase of laser power. When the laser power was 300 W, The microstructure of alloy was uniform, and the density and Vickers hardness of alloy were 8.19 g/cm³ and 345.6 HV, respectively. The laser transferred energy decreased with the increase of scan speed, which cause more holes and cracks in the alloy. The smaller scan speed, the larger width and smaller height of ichthyoid microstructure. When the scan speed was lower than 1400 mm/s, the L and H were about 110 μm and 50 μm respectively, and the solidified structure was uniform and dense.

1. Introduction
Additive manufacturing technology (3D printing technology) can realize complex part preparation, which is becoming an important development direction of advanced manufacturing technology due to its high ease of use, short cycle time, high precision, and low cost. In recent years, with the improvement of 3D technology and equipment, the raw materials of 3D printing have been expanded from low-melting organic materials to high-melting metal materials. Its application field has expanded from the simple model manufacturing to the forming of more complex and more difficult alloy structure [1-3]. Selective laser melting (SLM) as one of the most promising technologies in metal 3D printing, is increasingly used in medical, aerospace, aerospace, automotive parts manufacturing and related fields. The study about its process and performance has received extensive attention from researchers [4]. Selective laser melting is suitable for alloy powder materials with small particle size, and the microstructure and mechanical properties of the product are affected by the process parameters including powder characteristics, laser power, scan speed, etc. The study about the influence of technology parameter on the microstructure and mechanical properties of the alloy has important guiding significance for improving the performance of products [5].

GH4169 alloy is a high-temperature alloy with good yield strength below 650 °C, good fatigue resistance, radiation resistance, oxidation resistance, corrosion resistance and good processing performance. GH4169 alloy has been widely used in aviation, aerospace, nuclear energy, petrochemical and other fields due to the fact that it can manufacture complex parts [6]. At present, there are many types of SLM sintering equipment in China. However, the required powder materials have not yet formed a unified standard. Additionally, domestic research on SLM forming of GH4169 alloy powder mainly focuses on the research of SLM process parameters and the properties of
products, there are few studies on the adaptability of the properties of powders, the formed process and laser sintering equipment. In this paper, GH4169 powder was used as raw material, the morphology, microstructure and mechanical properties of products under different laser process parameters were analyzed, which expected to provide reference for the study on suitability and application research of GH4169 alloy powder and equipment.

2. Materials and methods

The experiment used aerosolized GH4169 powder with a median particle size of D (50) = 36.45 μm. The scan electron micrograph is shown in Fig. 1. It can be seen from Fig. 1 that the powder surface is smooth, the microstructure is uniform. Additionally, there is no obvious element segregation in the microstructure. Its chemical composition is shown in Table 1. The alloy powder was sintered by inert gas protection using an SLM apparatus, and after the powder was sintered and cooled. Then, the alloy was adopted wire cutting process to a size of 10 mm × 10 mm × 10 mm.

The surface morphology and microstructure of the specimens before and after the tests were also examined using the scan electron microscopy (FEI QUANTA 600) and optical microscope. The sample was etched with copper sulfate + hydrochloric acid + absolute ethanol etching solution. The density of the sample was measured by the Archimedes drainage. The hardness of the sample was measured by a micro Vickers hardness tester (402 MVA™). During the hardness test, 10 points were selected on the same line on the sample surface, and the load and holding time were 200 g and 20 s, respectively.

![Figure 1 SEM morphology of GH4169 powder](image1.png)

Table 1 Chemical composition analysis of GH4169 powder (wt %)

| Element | Weight Conc. (wt %) |
|---------|---------------------|
| Ni      | 53.25               |
| Cr      | 17.83               |
| Ti      | 0.70                |
| Al      | 0.28                |
| Nb      | 4.75                |
| Mo      | 3.31                |
| Fe      | Bal.                |

3. Results and discussion

3.1 The effect of laser power on the performance of alloy

The SLM process parameters have a significant impact on the performance of the product. The laser energy in the laser process is affected by laser power, scan speed, scan track spacing and spot diameter. The scan track spacing and laser spot diameter are depend on the SLM device used. Hence, the current research on process parameters focuses on laser power and scan speed. The experimental solutions for different laser powers are shown in Table 2.

![Table 2 Variation of laser power in laser sintering process](image2.png)
The density and relative density of 3D printed products under different laser power conditions are shown in Fig. 2. It can be seen from Fig. 2 that when the power is 100 W, the product density is 7.06 g/cm³, which is 85.7% of the theoretical density of GH4169 alloy (8.24 g/cm³). When the power is continuously increased from 200 W to 300 W, the density continues to increase from 7.58 g/cm³ to 8.19 g/cm³. When the laser power is 300 W, the relative density of the product reaches more than 99% of the theoretical density. It is clear that the density and relative density of the product increase with the increase of power, and the hardness of the product also appears the same trend of change. When the laser power is 300 W, the Vickers hardness reaches 345.6 HV, as shown in Fig. 3.

| Power (W) | Density (g/cm³) | Relative Density (%) |
|-----------|----------------|----------------------|
| 100       | 7.06           | 85.7                 |
| 200       | 7.58           | 96.8                 |
| 300       | 8.19           | 99.2                 |

Figure 2. Effect of laser power on density and relative density of alloy.

Figure 3. Effect of laser power on hardness of alloy.
Figure 4 Internal structure of alloy under different laser power (a) 100 W, (b) 200 W and (c) 300 W.

The internal structure of 3D printing products is shown in Fig. 4. It can be seen that there are many holes in the product, and the holes contain more un-melted spherical powder particles, under the condition of 100W laser power. When the power is increased from 200 W to 300 W, the porosity of the product decreases significantly, the microstructure is uniform, and there are no obvious pore, inclusion and un-melted particulate. Laser power is an important index reflecting the energy absorption of powder in sintering process. When the power is too low, the powder melts is incomplete, which cause un-fused defects and pore in the alloy. Hence, the laser energy absorbed by powder bed is insufficient and the wettability between the molten pool and the substrate is poor, which tends to form spherical particles. When the laser power is too high, the excess heat cannot be transferred in time, occurring over-burning phenomenon easily [7-9]. In this experiment, when the power is increased to 350 W, the splash during powder sintering is serious, and the product boundary collapses. Therefore, the appropriate laser power is about 300 W.

3.2 Effect of scan speed on properties of alloy

The experimental solutions for different scan speed are shown in Table 3. Fig. 5 shows the cross sections of four samples at different scan speed. It can be from Fig. 5 that the microstructures of the four products are homogeneous. Some holes and small cracks are found in the products when the scan speed is 2000 mm/s and 1800 mm/s, while there are no obvious holes or cracks in the products when the scan speed is 1400 mm/s and 1000 mm/s. It is clear that the number of holes in the products decreases with the decrease of scan speed. This is mainly attributed to the effect of scan speed on laser energy. The faster of the scan speed, the shorter of the time of the laser energy transfer. Hence, the laser energy is insufficient, which results in the failure of melt spreading. Finally, the joint between scan trajectory and trajectory appears, resulting in holes and cracks [10].

| Number | Scan speed (mm/s) | Layer thickness (μm) | Laser power (W) | Spot diameter (μm) |
|--------|-------------------|----------------------|-----------------|--------------------|
| 1      | 2000              | 20                   | 300             | 100                |
| 2      | 1800              | 20                   | 300             | 100                |
| 3      | 1400              | 20                   | 300             | 100                |
| 4      | 1000              | 20                   | 300             | 100                |
Figure 5 SEM of cross section of products at different scan speed (a) 2000 mm/s, (b) 1800 mm/s, (c) 1400 mm/s and (d) 1000 mm/s.

The microstructures of longitudinal section of products at different scan speed are characterized by SEM (as shown in Fig. 6), in order to research the effect of scan speed on the internal structure and morphology of the product. It can be seen from Fig. 6 the longitudinal section microstructures of GH4169 alloy are ichthyoid microstructure. When the scan speed is 2000 mm/s, the height H and width L of ichthyoid microstructure are 60 μm and 90 μm, respectively. The width of overlap between two solidified microstructure is less and there is obvious holes in the microstructure, as shown in Fig 6 (a). During SLM sintering process, the higher scan speed, the smaller size of molten pool, which leads to decreases the wettability and flow of molten pool. At the same time, the droplets in molten pool are easy to splash, and the microstructure spheroidization, un-fused defects and gas holes are easy to occur in the microstructures [11-14]. When the scan speed was low, the solidified structure was uniform and dense, the L and H were about 110μm and 50μm respectively, as shown in Fig. 6 (d). Because of the lower scan speed, the powder melts better and spreads more evenly in the forming process, which makes the final solidified structure wider and tighter bonding. Therefore, there are no obvious stomata and defects in the microstructures.
Figure 6 SEM of longitudinal section of products at different scan speed (a) 2000 mm/s, (b) 1800 mm/s, (c) 1400 mm/s and (d) 1000 mm/s.

4. Conclusion
(1) The density including relative density and Vickers hardness of SLM products increase with the increase of power. When the laser power increases from 100 W to 300 W, the density of SLM products increase from 7.06 g/cm³ to 8.19 g/cm³. The relative density reaches 99.4 % of the theoretical density, and the Vickers hardness of alloy is 345.6 HV when the laser power is 300 W. The microstructure of SLM products is uniform, and there are no obvious voids, inclusions and un-melted particles. When the laser power is 350 W, the product occur over-burns.

(2) The faster of the scan speed, the shorter of the time of the laser energy transfer. Hence, the laser energy is insufficient when scan speed is fast, which results in the holes and cracks in the microstructure. The number of holes and cracks in the products decreases when the scan speed decreases from 2000 mm/s to 1400 mm/s.

(3) During SLM sintering process, the higher scan speed, the smaller size of molten pool, which leads to decreases the wettability and flow of molten pool. When the scan speed is 2000 mm/s, the height H and width L of ichthyoid microstructure are 60 μm and 90 μm, respectively. When the scan speed was lower than 1400 mm/s, the solidified structure was uniform and dense, the L and H were about 110 μm and 50 μm, respectively.

References
[1] Lu Bingheng, Li Dichen. Development of Additive Manufacturing (3D Printing) Technology[J]. Mechanical Engineering & Automation, 2013, 42 (4): 1-4.
[2] Levy G N. The role and future of the Laser Technology in the Additive Manufacturing environment[J]. Physics Procedia, 2010, 5: 65-80.
[3] Yu Dongmei, Fang Ao, Zhang Jianbin. 3D Printing: Technology and Application [J]. Metal World, 2013 (6): 6-11.
[4] Yang Yongqiang, Liu Yang, Song Changhui. Current Status and Research Progress of 3D Printing Technology for Metal Parts[J]. Mechanical & Electrical Engineering Technology, 2013, 42 (4): 1-7.
[5] Fox P, Pogson S, Sutcliffe C J, et al. Interface interactions between porous titanium/tantalum coatings, produced by Selective Laser Melting (SLM), on a cobalt–chromium alloy[J]. Surface & Coatings Technology, 2008, 202 (20):5001-5007.
[6] Shi Changxu, Zhong Zengqi. Development and Innovation of Superalloys in China[J]. Acta Metall Sinica, 2010, 46 (11): 1281-1288.
[7] Louvis E, Fox P, Sutcliffe C J. Selective laser melting of aluminium components[J]. Journal of Materials Processing Technology, 2011, 211 (2): 275–284.
[8] Gu D, Hagedorn Y C, Meiners W, et al. Densification behavior, microstructure evolution, and wear performance of selective laser melting processed commercially pure titanium[J]. ActaMaterialia, 2012, 60 (9): 3849-3860.
[9] Xie X S, Dong J X, Zhang M C, et al. High Temperature Structure Stability Study on Nb-Containing Nickel-Base Superalloys[J]. Materials Science Forum, 2007, 546
[10] Li D C, He J K, Tian X Y, et al. Additive manufacturing: integrated fabrication of macro/microstructures [J]. Journal of Mechanical Engineering, 2013, 49 (6): 129-134.

[11] Lü L, Fuh J Y H, Wong Y S. Laser-induced materials and processes for rapid prototyping [M]. Singapore: Springer Science & Business Media, 2013.

[12] Song B, Zhao X, Shuai L I, et al. Differences in microstructure and properties between selective laser melting and traditional manufacturing for fabrication of metal parts: A review [J]. Frontiers of Mechanical Engineering, 2015, 10 (2): 111-125.

[13] Shiomi M, Osakada K, Nakamura K, et al. Residual stress within metallic model made by selective laser melting process [J]. CIRP Annals-Manufacturing Technology, 2004, 53 (1): 195-198.

[14] Mercelis P, Kruth J P. Residual stresses in selective laser sintering and selective laser melting [J]. 2005 Solid Freeform Fabrication Symposium, 2005, 06-08 (8): 254-265.