Mechanical Properties of GH4169 superalloy Prepared by Selective Laser Melting

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Abstract. Using selective laser melting technique, 3 sets of GH4169 samples were formed by various laser power and scanning speed to prepare mechanical properties test specimens. The defects and porosity of the samples were measured by CT inspection. The tensile test was carried out at room temperature. The fracture morphology of the tensile samples was observed by SEM and the fracture mechanism was analyzed. The results show that some samples have pores with largest size of 100μm, which have no effect on the subsequent tensile properties test. The tensile strength does not change significantly with the varying process parameters, and the highest strength could reach 1480MPa. The elongation and the reduction of area decrease gradually as the scanning speed increases, indicating that the plasticity of the material is descending. The fracture mechanism of the three sets specimens are ductile fractures, and the microscopic morphology shows distribution of equiaxed dimples.

1. Introduction
Selective Laser Melting (SLM) can directly layer and overlie parts using 3D model. It is a promising method of additive manufacturing technology [1, 2]. It uses direct laser beam reacting on the powder material, to melt the material and solidify quickly. With its layered manufacturing characteristics, it does not require any fixtures and molds, and is suitable for processing parts with complex structures [3]. At the same time, SLM has high forming precision and good surface quality, which can achieve net shaping or near net shaping of parts [4]. Due to its high energy density which enables it to process a variety of high-melting point materials, SLM technology has been widely used in manufacturing nickel-based alloys [5].

High-temperature nickel-based alloy GH4169 (Inconel718) is an ageing precipitation strengthening alloy with γ-Ni phase as matrix, γ' and γ'' phase as strengthening phase, in addition to δ phase act as equilibrium phase of γ'' phase [6]. Also there are other compounds such as NbC and TiN. GH4169 alloy has good strength, oxidation resistance and corrosion resistance. It has excellent reliability serving in high temperature environment. It is often used in the manufacture of hot end parts and is widely applied in aviation, aerospace, energy and other fields [7]. However, GH4169 has the processing characteristics of severe cut hardening. When processing complex components, it will affect the mechanical properties of the formed parts, while SLM can effectively reduce the processing difficulty, and at the same time it can meet the mechanical properties requirements.

Many scholars have studied the manufacture of GH4169 material prepared by SLM technology and obtained some conclusions. Polish scholar E. Chlebus, found that the formed samples under the heat treatment of solid solution and aging have better mechanical properties than forging parts [8]. Swedish
scholar Dunyong Deng compared the tensile strength of horizontal and vertical deposited samples and concluded that heat treatment can increase the tensile strength of the sample [9]. Most of the current research focus on the effect of deposition angle of the parts and heat treatment on the tensile properties of the samples. However, the study on the influence of process parameters on the tensile strength of SLM-prepared GH4169 samples is rare.

In this article, GH4169 was used as experimental material to prepare samples by SLM with different process parameters. The mechanical properties of the formed samples were measured by room temperature tensile test, which can provide a theoretical basis for SLM manufacturing GH4169 aerospace components.

2. Experimental procedures

2.1. Experiment Equipment
The SLM system in this study uses the M290 equipment from EOS company of Germany, equipped with a 400w fiber laser, adopts layered slice data from CAD model, and uses a laser beam to sinter the ultrafine metal powder in layers to form a complex structure.

2.2. Experiment materials
The GH4169 powder used in this research is prepared by the rotating electrode method, and the powder size is 15-49 μm. The morphology is shown in Figure 1. The fluidity is good, and the entire substrate could be evenly covered during the powder spreading process. The nominal composition and tested composition results of the powder are shown in Table 1.

![Figure 1. Morphology of GH4169 powder.](image)

Table 1. The nominal composition and tested composition of GH4169 powder

| Elements | C    | Cr  | Ni  | Co  | Mo  | Al  | Ti  | Nb  | Fe  |
|----------|------|-----|-----|-----|-----|-----|-----|-----|-----|
| Nominal  | 0.02~| 17.0~| 50.0~| ≤1.0| 2.80~| 0.30~| 0.75~| 5.00~| Bal.|
| composition| 0.06 | 21.0 | 55.0 | ≤1.0| 3.30 | 0.70 | 1.15 | 5.50 | Bal.|
| Tested | 0.036 | 18.70 | 53.83 | <0.10| 3.23 | 0.44 | 0.93 | 5.19 | Bal.|

2.3. Experiment process
The experiment uses three sets of process parameters, 1#: 260W, 0.9m/s, 2#: 290W, 1.2m/s, 3#: 350W, 1.5m/s, and the power density of the three sets is gradually reduced (The power density is defined as laser power/scanning speed), other parameters are the same for the three sets. The scanning pitch is 0.11 mm, the thickness between the adjacent layers is 0.04 mm, and the spot diameter is 0.1 mm. In the previous research, the three sets of process parameters can achieve sample density of more than 99%. Four samples were formed for each set of process parameters, as shown in Figure 2a.

After the depositing, the samples were cut off from the substrate by wire cutting, and then the samples were subjected to solid solution + double-stage aging. The heat treatment condition is
980°C for 1h, air cooled to room temperature, and 720°C for 8h and then with the cooling rate of 50°C/h cooled to 620°C for 8h, then air cooled to room temperature. After the heat treatment, the tensile specimens were prepared according to the standard Q/6S977-2004, as shown in Figure 2b. CT inspection was also performed before the mechanical properties test to verify that the samples were not affected by the porosity. The test samples were then subjected to a room temperature tensile test using a AG-250KNIC tensile tester, and the fracture morphology of the sample was observed by JSM-7610Plus scanning electron microscope.

![Figure 2. (a) Photo of 3 sets tensile test samples, (b) The sample pattern of tensile testing.](image)

3. Results and Discussion

3.1. CT detection

Before the mechanical property test, one sample was selected from each process set to do micro-nano CT for quality evaluation. The cross-section slices obtained from the micro-nano CT inspection are shown in Figure 3.

![Figure 3. CT slices of various process sets, (a), (b), (c) are transverse slices of respectively, (d), (e), (f) are longitudinal slices of 1#, 2#, 3#](image)

It can be seen from Figure 3 that the GH4169 sample formed under the 1# parameters has no micro-pores and defects. And the micro-pores with a maximum of 0.1 mm are detected in the samples formed under parameters 2# and 3#. According to the literature [10, 11], the micro-pores and defects less than 200 μm of test sample have little effect on the tensile properties. Therefore, it is considered that the microstructure quality of the three sets samples has no effect on the mechanical properties test.

3.2. Tensile test

The samples subjected to the tensile test were deposited from three sets of process parameters, and four samples were tested for each set of process parameters. The test results are averaged and the
sample variances are calculated shown in Figure 4. It can be seen that the tensile strength of the 2# set (1480MPa) and the 3# set (1477MPa) is slightly improved compared to the 1# set (1450MPa). In the yield strength plot, similar trends can be found, 1# set (1247MPa), 2# set (1280MPa), and 3# set (1278MPa). The tensile strength improvement ratio is about 2.1%, and the yield strength improvement ratio is about 2.7%, which is not significant and can be considered as fluctuation within the error range. From the perspective of heat treatment, the three sets of samples were subjected to the same solid solution strengthening and ageing precipitation strengthening, which promoted the homogenization of microstructure and the precipitation behavior of strengthening phase, so the three sets of samples reached the approximate tensile properties. In systematic analysis, the selected process parameters have little effect on the tensile strength and yield strength of the formed samples.

![Figure 4](image_url)  
**Figure 4.** Average tensile strength and yield strength of 3 process parameters sets

![Figure 5](image_url)  
**Figure 5.** Average elongation and reduction of area of 3 process parameters sets

It is shown in Figure 5 that the average elongation and reduction of area of the three sets samples have a large drop, and the variation rate of the adjacent sets exceeds 10%. This indicates that the plasticity of the samples is declining, with the order of 1#>2#>3#. From the perspective of forming process, 1# parameters: 260W, 0.9m/s; 2# parameters: 290W, 1.2m/s; 3# parameters: 350W, 1.5m/s, the power density of three sets decreases very slightly, which may not explain the plasticity decrease. The scanning speed is increased with large amplitude, indicating that the metal material undergo a process of rapid melting, rapid cooling and solidification during the process. Therefore, when the scanning speed is gradually increased, the rapid cooling and solidification generates a large internal stress in the formed part, and deforming the local structure of the part, resulting in an increase in the dislocation density. The mutual cross of dislocations during the movement is intensified. As a result, jogs, dislocation entanglements and other obstacles are generated, which increases the resistance of dislocation motion, causes the deformation resistance to increase, hinder the plastic deformation, and the plasticity of the parts declines. Therefore, the increase in the scanning speed causes decrease in the plasticity of the formed sample.
3.3. Fracture analysis

One sample of each set was selected for sample fracture analysis, and the macroscopic morphology of the fractures was observed by scanning electron microscope as shown in Figure 6.

It can be observed from Figure 6 that the GH4169 tensile fracture is a shear-slip fracture. The expansion area of the entire fracture surface accounts for a large proportion, and the shear lip area has a smaller ratio, which indicates that the sample is ductile fracture with good plasticity.

Figure 7 shows the high-magnification morphology of the GH4169 tensile fracture at room temperature from different process sets. The fracture morphology shows fibrous macroscopically and has honeycomb shape in micro. From the figure, the equiaxed dimples of the tensile fracture can be observed. In addition, the granular precipitate phase exists in the dimple, which can be inferred to be MC with detection by EDS. The fine and dense dendrite microstructure and the dispersed MC phase promote the fracture to present a large number of fine and uniform dimple features.

4. Conclusion

In this article, GH4169 samples were prepared by selective laser melting with 3 sets of process parameters. The pores and defects were verified by CT inspection. The tensile test was carried out on the samples and the tensile fracture morphology was analyzed.

1) Through CT inspection, the sample formed by process parameter 1# has almost no defects and pores. The samples formed by process parameters 2# and 3# have pores with maximum size of 100 μm. This pore size has no effect on the subsequent tensile properties.

2) The tensile strength and yield strength of the samples of different process parameters show less variation. After the same solid solution strengthening and age strengthening, the three sets of samples obtained similar strengthening effects, and the tensile properties can be up to 1480MPa.

3) The elongation and reduction of area of the three sets samples gradually decrease, indicating that the plasticity is diminished. As the scanning speed increases, the stress and deformation of the formed samples rise, and the samples subjected to deformation hardening effect and its plasticity is lowered.

4) The fractures of the three sets samples are macroscopically fibrous, and have honeycomb-shaped dimples microscopically. The fracture mechanisms are judged to be ductile fracture.
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