Process Optimization and Microstructure Characterization of Ti6Al4V Manufactured by Selective Laser Melting

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Abstract. Process optimization and microstructure characterization of Ti6Al4V manufactured by selective laser melting (SLM) were investigated in this article. The relative density of sampled fabricated by SLM is influenced by the main process parameters, including laser power, scan speed and hatch distance. The volume energy density (VED) was defined to account for the combined effect of the main process parameters on the relative density. The results shown that the relative density changed with the change of VED and the optimized process interval is 55~60 J/mm³. Furthermore, compared with laser power, scan speed and hatch distance by taguchi method, it was found that the scan speed had the greatest effect on the relative density. Compared with the microstructure of the cross-section of the specimen at different scanning speeds, it was found that the microstructures at different speeds had similar characteristics, all of them were needle-like martensite distributed in the β matrix, but with the increase of scanning speed, the microstructure is finer and the lower scan speed leads to coarsening of the microstructure.

1. Introduction

Ti6Al4V, a kind of titanium alloy, is a typical two-phase alloy. With a reputation of corrosion resistance, high specific strength and so on. Ti6Al4V is called “space metal” or “ocean metal”, due to its excellent performance and a wide application prospect in the military and civilian industry [1]. With the wide application of titanium alloy in biological and medical fields in recent years, it is a general trend to fabricate complex structure of Ti6Al4V alloy device [2-4]. However, conventional manufacturing technology is unable to meet the requirements in the manufacturing of complex structure, such as internal channel, space gradual changing surface and ultrathin wall.

To break the bottleneck, metal additive manufacturing technologies have, therefore, been developed, especially Selective laser melting (SLM) technology. It melts the powder layer by layer, forming a good metallurgical bonding between the layers without any auxiliary tools. Theoretically, it can form a completely dense and any complex components. However, there are many factors during the process of SLM, causing it is difficult to obtain fully dense component [5, 6]. Therefore, improvement of density of samples fabricated by SLM has become a main concern for many scholars. In addition, special microstructure due to extreme non-equilibrium state during process of SLM also has been noticed. Sun J et al. have conducted a optimization of parameters of Ti6Al4V fabricated by SLM using Taguchi method [7]; defect has been discussed via experimentally studied and defect generation mechanisms were different at too high or too low of energy input [8]; Shi X et al. have investigated influence layer thickens on performance with a high layer thickness (200μm) [9]; Khorasani A M et al. have discussed the mechanisms and critical parameters on solidification, such as laser power, scan speed and strategy, layer thickness, hatch spacing [10]; Kabir M et al. proposed a comprehensive model to help understand the interaction between process parameters, pore
morphology and mechanical properties [11]; Song B et al. have investigated process parameters based temperature distribution simulation model [12]; Process parameters of AlSi10Mg fabricated by SLM were conducted by Kempen K et al. [13]. Porosity content control of CoCrMo fabricated by SLM was studied by Joguet D et al. [14]; Thijs Lore et al. have investigated the development of microstructure of Ti6Al4V alloy processed by SLM at different scan strategies [15]; Han J et al have studied microstructure of the SLM processed Ti6Al4V at various laser energy densities [16]. It can be seen that the process parameters are the key factors which affect the defect and microstructure of samples fabricated by SLM, and it is still need to conduct the process optimization of Ti6Al4V fabricated by SLM.

This paper aims to investigate the effect of process parameters (laser power, scan speed, and hatch distance) on relative density of Ti6Al4V manufactured by SLM, and obtain a suitable process parameter range; Subsequently, Taguchi method was used to study the influence degree of three process parameters on relative density. Further, the microstructure under different scan speed was investigated.

2. Experiment and method

Gas atomized Ti6Al4V powders was used in this investigation. The morphology of powder as shown in figure 1. A near spherical shape was present in figure 1 and the surface of powder was not smooth as presented in figure 1(b). Process parameters used in this experiment was shown in table 1. The layer thickness (LT) used in the experiment was kept in 0.03mm. The scan strategy used in this experiment and the sample (6mm×6mm×6mm) processed by SLM were described in figure 2.

### Table 1. Process parameters used in the experiment.

| Parameter                  | Level 1 | Level 2 | Level 3 |
|----------------------------|---------|---------|---------|
| Laser power/(LP, W)        | 280     | 300     | 320     |
| Scan speed/(SS, mm/s)      | 2800    | 3000    | 3200    |
| Hatch distance/(HD, mm)    | 0.05    | 0.06    | 0.07    |
| Layer thickness/(LT, mm)   | 0.03    | 0.03    | 0.03    |
All parts were fabricated on the self-developed SLM 150 machine. This SLM machine is equipped with an IPG YLR-400 fiber laser, which produces a laser beam with a wavelength of 1070nm and can reach a maximum power of 400W in continuous mode. The scanning velocity can be varied from 10 to 7000mm/s, the maximum diameter of the useful building area is 150mm×150mm. The building chamber is first evacuated and then filled with an inert argon atmosphere to keep an atmosphere with a low oxygen content during building.

The relative density was measured based on Archimedes principle by weighing the samples in the air and subsequently in water. Standard metallographic process was conducted for microstructure, and a solution of 80 ml H₂O, 5 ml HF and 10 ml HNO₃ was used to reveal microstructure. Microstructures were observed under an optical microscope (Nikon MA 200). Morphology of Ti6Al4V powder was characterized by SEM (Hitachi, S4800).

3. Results and discussion

3.1. Process optimization of Ti6Al4V fabricated by SLM

Part density is one of the most important factors to optimise, for it has a direct correlation on the part’s mechanical and physical properties. Volume energy density (VED) was defined to describe the relationship between relative density and the combination of three factors. The equation as follows:

\[
\text{VED} = \frac{LP}{(SS \cdot LT \cdot HD)}
\]

The relationship between relative density and VED was depicted in figure 3. With the increase of VED, the relative density increased first and then decreased. When the VED is near 60J/mm³, the relative density reaches the maximum value, which is close to 100%. There are two reasons for this phenomenon. Figure 4 shows the melting path profile under different LP/SS, when the LP/SS value is too low, as shown in figure 4(a) the depth of the melting channel is lower and spheroidization occurs, resulting in a weak bonding between the layers and un-melted powder particles, therefore the relative density is low; When the LP/SS value is too high, as shown in figure 4.(b) the melting track depth is too large, the height is smaller, it is difficult to form, and the phenomenon of element evaporation and ablation is easy to occur during the forming process, and the density decrease is also caused. Figure 5 shows the melting path profile under different HD. When Hatch distance is too large, the overlap area of molten track is too small, as shown in figure 5(a), which leads to the partial melting of the powder and the inclusion occurred; the phenomenon of porosity results in the appearance of evaporation and ablation of elements after overlap, as shown in figure 5(c). Therefore, only the suitable LP/SS and HD can obtain higher relative density, as shown in figure 4(b) and figure 5(b).

![Figure 3. Variation of relative density under different volume energy densities.](image-url)
3.2. The Influence degree of three factors on relative density
After optimizing the manufacturing process, the influence degree of the three factors on the relative density was studied by Taguchi method. Table 2 illustrates the S/N results of the cubic samples produced in the experiment. According to the range analysis from S/N, the influence degree of each factor on the density is Scan speed>Hatch distance>Layer power. Figure 6 shows the change curve of S/N main effect value and the change trend density with various factors.

Table 2. Responses for density and the corresponding S/N.

| Std. | A:LP/(W) | B:SS/(mm/s) | C:HD/mm | RD/% |
|------|----------|-------------|---------|------|
| 1    | 280      | 2800        | 0.05    | 95.25|
| 2    | 280      | 3000        | 0.06    | 96.89|
| 3    | 280      | 3200        | 0.07    | 89.55|
| 4    | 300      | 2800        | 0.05    | 92.86|
| 5    | 300      | 3000        | 0.06    | 98.55|
| 6    | 300      | 3200        | 0.07    | 90.78|
| 7    | 320      | 2800        | 0.05    | 90.42|
| 8    | 320      | 3000        | 0.06    | 99.69|
| 9    | 320      | 3200        | 0.07    | 93.02|
| S/N-1| 39.45    | 39.38       | 39.57   |
| S/N-2| 39.46    | 39.86       | 39.48   |
| S/N-3| 39.49    | 39.19       | 39.35   |
| Range| 0.04     | 0.67        | 0.22    |

Figure 6. S/N main effect graph.
3.3. Microstructure characterization of Ti6Al4V fabricated by SLM

Microstructure has a direct influence on mechanical properties of components. Therefore, microstructure of samples fabricated by SLM at different scan speed was characterized. Due to the special building process, the microstructure of SLM processed sample is quite different with other traditional manufacturing technology, such as welding, casting, as shown in figure 7. As expected the present microstructure mainly is a very fine acicular martensite, due to the fast cooling rate that occur during the SLM manufacturing process. However, the effect of utilized scan speed on thermal histories during fabrication and, consequently, the resultant microstructure of part had still some differences. With the increase of scan speed, the refined acicular martensite appeared in the matrix of β. This can be due to the fact that the different cooling rates experienced during fabrication at different scan speed may result in different microstructures; That is, the increase of scan speed leads to an increase in the cooling rate, which in turn results in a finer microstructure. The lower scan speed thus results in a coarser microstructure.

![Microscope images of the cross-sectional surface of Ti6Al4V samples manufactured at different scan speed (red line is the boundary of β matrix).](image)

**Figure 7.** Microscope images of the cross-sectional surface of Ti6Al4V samples manufactured at different scan speed (red line is the boundary of β matrix).
4. Conclusion
In this study, effects of process parameters (i.e. laser power, scan speed and hatch distance) on relative density of Ti6Al4V samples manufactured by selective laser melting (SLM) and microstructure corresponding to different scan speed were investigated. It was found that the relative density of Ti6Al4V samples manufactured via SLM was greatly influenced by process parameters. Volume energy density (VED) was defined to show the combined effect of process parameters, and the optimized VED interval is 55~60J/mm$^3$. The influence of three process parameters (i.e. laser power, scan speed, hatch distance) on the relative density was studied by Taguchi method. It was found that among the three process parameters, scan speed had a greater effect on relative density. Furthermore, microstructure characterization shown that with the increase of scan speed, the refined acicular martensite appeared in the β matrix. This can be due to the fact that the different cooling rates experienced during fabrication at different scan speed may result in different microstructures. The lower scan speed thus results in a coarser microstructure. In a word, the purpose of this paper is to optimize the process parameters and microstructure characterization of Ti6Al4V fabricated in the self-developed SLM equipment. It is found that the nearly dense Ti6Al4V component can be realized and the microstructure can be controlled by the process parameters. The customization of the microstructure may be obtained by the design of process conditions.

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