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Manufacturing feasibility and forming properties of V-6Cr-Ti alloy by selective laser melting

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Abstract. Vanadium alloy has received a great deal of attention in applications for fusion reactors. The selective laser melting (SLM) offers a new processing candidate. In this study, it is evaluated for the manufacturing feasibility and forming properties of V-6Cr-Ti alloys by SLM technology. The macroscopic quality, the densification mechanism and surface roughness of samples were investigated. The effect of laser processing parameters, including laser power, laser scanning speed and laser energy density, on the properties of samples were also researched. It was found that the laser scanning speed and laser power have important influence on the relative density. There is no obvious relationship between process parameters and surface roughness. These results demonstrate that SLM process can be used to manufacture V-6Cr-6Ti components with feasibility.

Key words. Selective laser melting, V-6Cr-Ti alloy, processing parameters, forming properties
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1. Introduction

With the continuous growth of human demand for energy and the reduction of energy reserves such as coal, oil and natural gas, the exploration of nuclear energy has caused widespread concern. The construction of nuclear reactors is an important approach to solve the world's energy problems. Vanadium alloys are important candidates for fusion reactor construction materials due to its excellent low activation

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characteristics, high temperature plasticity, good corrosion resistance to liquid metals such as lithium, sodium and potassium, and excellent dimensional stability under irradiation[1]. Meanwhile, Vanadium alloys own excellent mechanical properties[2]. For example, vanadium alloys have been used as the first wall and cladding materials in the International Thermonuclear Experimental Reactor (ITER) project.

Selective laser melting (SLM) is an additive manufacturing technology, which can directly produce components from a three-dimensional CAD model without sequential process. By using a computer-controlled scanning laser beam, the SLM process can selectively fuse and melt layers of metal powder to prepare components. Because of its flexibility, SLM represents a potential to produce parts, which are complex in shape and cannot be manufactured using conventional machining techniques. The combination of high design flexibility, excellent process capabilities, and high mechanical strength makes this technique more attractive to industrial manufacturers[3]. So far, there is almost no report on manufacture V-6Cr-6Ti alloy by SLM technology. In addition, vanadium alloy is very expensive and SLM process will not waste more material, which will greatly reduce costs. Vanadium alloy parts usually need only single or small batch production, which meet the advantage of SLM process.

In the present study, V-6Cr-6Ti alloy powder was selected for SLM under different processing parameters. The effects of energy density, laser power and scanning speed on the mechanical property were investigated. This study finds that SLM was able to produce a relatively high density vanadium alloy with irregular powder particle shape and a broad range of powder particle size.

2. Experimental details

2.1. Materials

The V-6Cr-6Ti powder with the main chemical composition of V 88 %, Cr 6 %, and Ti 6 % was selected [2]. In the present study, V-6Cr-6Ti powder was produced by ball milling. The average particle size and the particle size distribution were measured using a Mastersizer 2000 LaserParticleAnalyser, as shown in Fig.1. The medium diameter (d0.5) of powder is 29.725 ??m, d0.1 and d0.9 of powder are 8.303μm and 67.897μm, respectively.Fig.2 shows the morphology of theV-6Cr-6Ti powder. The powder shape is polygonal and quasi-spherical.

2.2. fabricating pcocess

The SLM experiment was performed in a commercial EOSINT M280 machine (EOS GmbH - Electro Optical Systems, Germany) which mainly consisted of a continuous wave fibre laser with a wave length of 1,070nm. The main characteristics of the EOS M280 machine are as follows: the maximum laser power is 200W; the maximum laser scanning speed is 7,000 mm/s; the laser spot size is 100μm; and the maximum process dimension is (L×W×H): 250×250×300 (mm). The SLM was processed in an enclosed argon environment with an oxygen content of less than 0.1%.

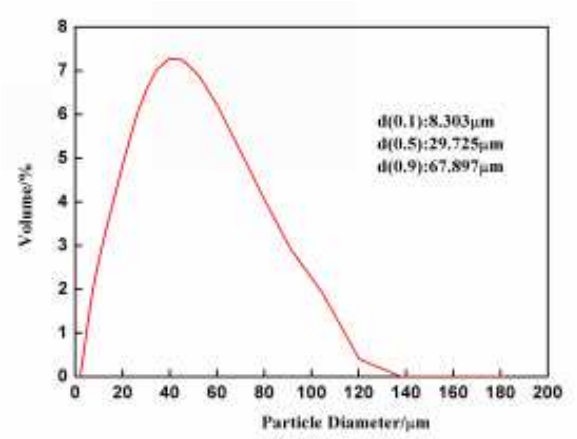

Fig. 1. Particle size distribution of V-6Cr-6Ti powder

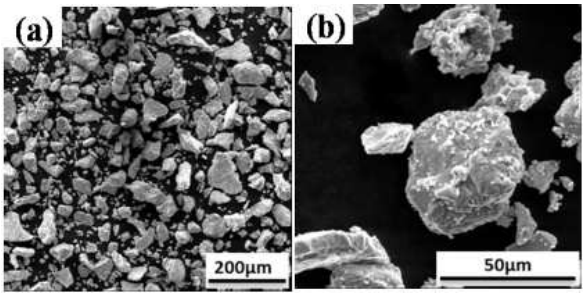

Fig. 2. Morphology of V-6Cr-6Ti powder

The base plate temperature in the processing was 35?C. Each powder layer thickness was 30μm, and a hatch spacing of 100μm was set for this study. The cubic specimens with the dimension of (10mm length×10mm width×4mm height) were manufactured on a Ti-based substrate. Two groups of parameters were designed to investigate the effect of those parameters on the mechanical properties of the specimens. In group 1, the laser power was constant (P=180W) and the laser scanning speed increased from 700mm/s to 1,300mm/s at a increments of 150mm/s, as shown in Table 1. In group 2, the laser scanning speed was constant (P=1,000mm/s) and the laser power increased from 160W to 200W at increments of 10W, as shown in Table 2.

Table 1. Parameters with different laser scanning speed of group 1

Piece	N1	N2	N3	N4	N5
Scanning speed(mm/s)	700	850	1000	1150	1300
Power(W)	180	180	180	180	180
Energy density(J/mm^3)	85.7	70.6	60.0	52.2	46.2

Table 2. Parameters with different laser scanning speed of group 2

Piece	N6	N7	N8	N9	N10
Power(W)	160	170	180	190	200
Scanning speed(mm/s)	1000	1000	1000	1000	1000
Energy density(J/mm3)	53.3	56.7	60.0	63.3	66.7

2.3. Characterisation

The dimensions and weight were measured to a precision of 0.01mm and 0.001gre-spectively. Each processing condition was repeated at least three times and the result of the density measurement was expressed using the mean value. The cross-sectional (X-Y, i.e. the laser melting layer plane) and longitudinal (X-Z, i.e. the building direction plane) microstructures of the samples were examined by mounting the samples in epoxy and polishing by using standard metallographic procedures. The samples were etched with a solution consisting of 75% nitric acid and 25% hydrofluoric acid and studied by scanning electron microscopy.

3. Results and discussions

3.1. Macroscopic quality

Fig. 3 shows the top and side surface of the samples. It is obvious that ten samples with different parameter combinations were manufactured successfully, which indicates that SLM technology is suitable for the manufacture of vanadium alloy parts. There is nearly no difference in macro morphology between the two samples of each parameter. This illustrates that SLM technology has repeatability in the manufacturing of vanadium alloy parts. However, there is a big difference between the samples in the macro morphology, as shown in Fig.3(a) and (b).The sample N1 has a rougher top surface than the others, and defects can be found in samples N5 and N6 in Fig.3(c) and (d),which indicate that different parameter have a great influence on the quality of the sample. So, it is necessary to make a further investigation into the impact of the parameters on different mechanical properties.

3.2. Densifications

Fig.4 shows that the relative density of SLM-processed V-6Cr-6Ti parts changed with various energy densities. As illustrated, there was not a linear relationship between relative density and various energy densities. For a given SLM-processed material, the energy density of the laser (E) is an important factor which has a high impact on the quality and density of the parts. The volumetric energy density (E) was defined by[4, 5]:

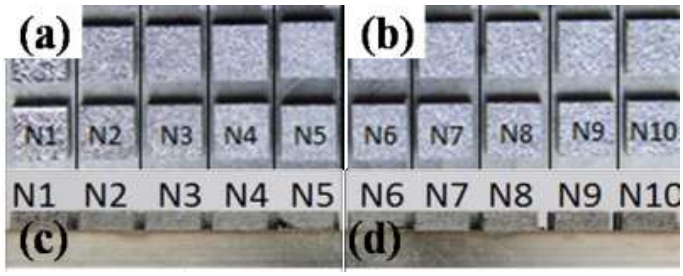

Fig. 3. Top and side surface of samples: (a) top surface of group 1; (b) top surface of group 2; (c) side surface of group 1; (d) side surface of group 2

$$\mathrm{E} = \frac{\mathrm{P}}{\upsilon \mathrm{ht}}$$

Where P is the laser power (in W), the laser scanning speed (in mm/s), h the hatching distance (in mm) and t the layer thickness (in mm). As a general rule, an increase in energy density results in a large amount of melting during the process. But other important factors, like reflection, absorption, evaporation and emission of material, heat transfer and phase transformation lead to a non-linear response between the energy density and sample densification[6]. Therefore, it is important to establish the links between the manufacturing parameters of the SLM process (i.e. laser power and laser scanning speed) to minimize balling effects and instability of the molten pool, which have been reported as undesirable phenomena during SLM[7].

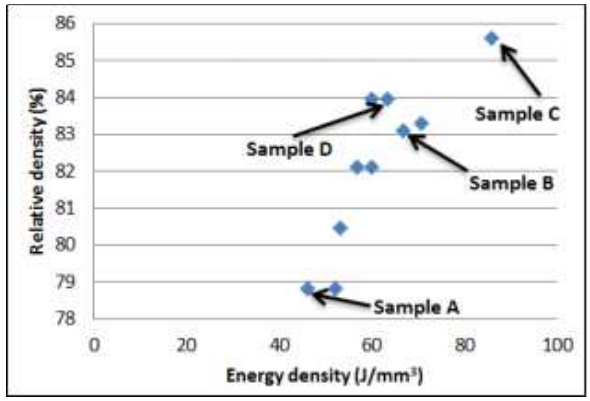

Fig. 4. Relative density of the V-6Cr-6Ti parts processed by SLM at various energy densities

Fig. 4 shows that a large number of samples with high relative densities (>80%) were obtained when the energy density was larger than 52J/mm^3. There was an increase in relative density from 78.81% to 85.6% when laser power increased from 46.2J/mm^3 to 85.7J/mm^3. However, sample B which have higher energy density than sample D because some combinations of laser power and laser scanning speed

were either not able to melt all the powder layer or to make stable molten pool due to the irregularity of the liquid pool, over heating of the powders and balling effects, as shown in Fig. 5. This demonstrates that there are the important links between manufacturing parameters at various energy densities. However, it was evident that a higher laser energy density was required to provide sufficient heating energy for full melting of the powders.

In order to further investigate the SLM-processed vanadium alloy parts, three samples (A, B and C) processed at three different conditions were selected. The parameters are as follows: sample A (P=180W, v=1300mm/s, and relative density=46.2J/mm^3), sample B (P=200W, v=1000mm/s, and relative density=66.7J/mm^3) and sample C (P=180W, v=700mm/s, and relative density=85.7J/mm^3).The effect of laser energy density on the densification of samples from both cross-sectional and longitudinal views is shown in Fig. 5.

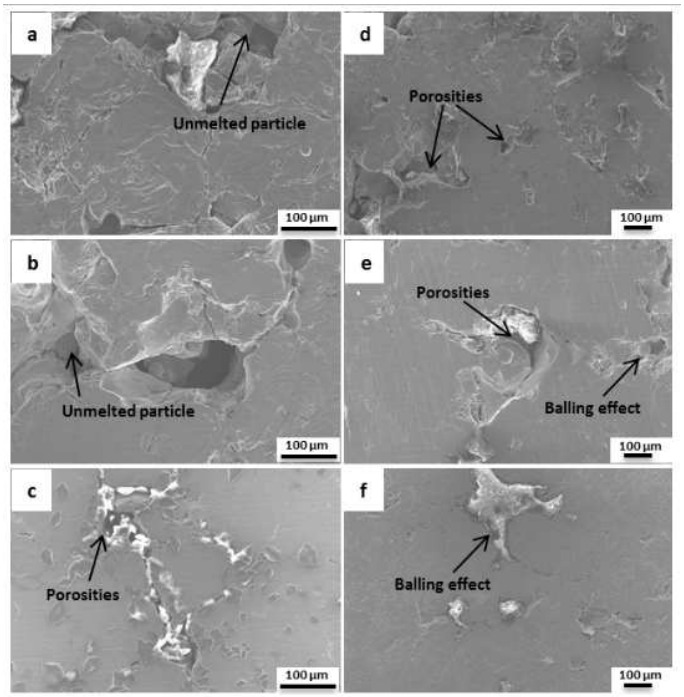

Fig. 5. SEM cross-sectional (X-Y) microstructures: (a) sample A, (b) sample B, (c) sample C, and longitudinal (building direction, Z) microstructures: (d) sample A, (e) sample B, (f) sample C. Processing conditions were: sample A (P=180W, v=1300mm/s, and relative density=46.2J/mm^3), sample B (P=200W, v=1000mm/s, and relative density=66.7J/mm^3) and sample C (P=180W, v=700mm/s, and relative density=85.7J/mm^3)

A large number of un-melted particles and porosities were observed in sample A and B. This may be related to the incomplete melting of the powders due to insufficient laser energy density. The balling effect was observed in sample B and sample C. This could be caused by the overheating of the powders. Porosities were

also observed in sample C due to non-optimal SLM manufacturing parameters and material properties of the powder. However, the porosities were smaller and less with the increase of the laser energy density, which also indicates that higher laser energy densities are required in order to process a sample with high densification.

As illustrated in Fig. 4, there is not a linear relationship between relative density and energy density. For example, sample B with higher energy density than sample D have a lower relative densities. So, it was necessary to investigate the links between each manufacturing parameter and the relative density of the samples.

The relationship between the laser scanning speed and the relative density of samples is shown in Fig. 6(a) and the laser power is constant at 180W. As illustrated, the relative density decreased from 85.6% to 78.8% when the laser scanning speed was increased from 700mm/s to 1,300mm/s. There was nearly no difference in the relative density between the two samples when the laser scanning speed was1,150mm/s and1,300mm/s, which may be due to its lowest point. There are damaged appearance and split between the sample N5 and substrate. It is possible that the relative density will be increased if the laser scanning speed is decreased less than 700 mm/s. But this increase may be slight because overheating of the powders and balling effects were found in sample N1 in Fig. 4. Of course, this needs to be verified in a future investigation.

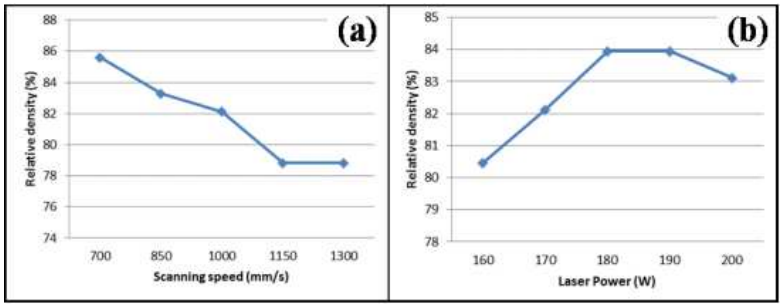

Fig. 6. Relationship between the laser parameter and the relative density of samples: (a) laser scanning speed; (b) laser power

Fig. 6(b) shows that there was an increase in relative density from 80.46% to 83.94% when the laser power increased from 160W to 180W at a constant scanning speed of 1,000 mm/s. Increasing the laser power to 200 W did not further increase the density, on the contrary, causing the relative density to decrease. It appears that once the material has been melted completely and there was no benefit in increasing the laser power further, which may lead to detrimental phenomena such as the balling effect or evaporation[4].

When the laser scanning speed is constant (1,000mm/s), the maximum relative density of the sample was found reach 83.94% and it cannot be increased by change the scanning speed. Compared with other SLM metal samples, such as Ti6Al4V, steel, Al, etc., which have nearly 100% relative density, this may be caused by the irregular powder morphology and large particle size distribution. Spieringset. al [8] reported that particle size distribution of a metallic material had a high impact on the

density of the SLM-produced parts. Spherical or near spherical particles generally resulted in close apparent density, thereby leading to a more efficient densification during the SLM process [9].

3.3. Surface roughness

Surface roughness was measured by the XYZ rapid scanning method. The measure scope was $2583\times2582\mu$m and the scanning line is shown in Fig. 7. The effect of the laser scanning speed and the laser power on the top and side surface roughness is shown in Fig. 8. No obvious relationship between the process parameters and the surface roughness could be found. However, the top surface roughness is always larger than the side roughness, which is also different to other studies[10]. This may be due to the irregular powder particle shape and the broad range of powder particle size, which can lead to a poor flow-ability[9,11].

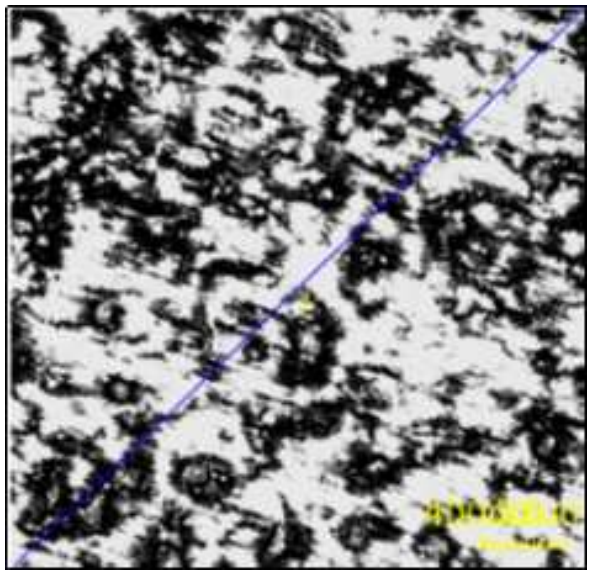

Fig. 7. Scanning line of surface roughness measurement

For N1, the delivered energy density of the laser beam was extremely high in the processing parameters (v=700mm/s, p=180 W) during the experiment. There are much powder was evaporated due to the temperature over the boiling point of V-6Cr-6Ti and inhaled into the filter system. Finally, compared with other parts, the surface roughness is worse.

4. Conclusions

The combination of different laser parameter have a great influence on the quality of the sample. A large number of samples with high relative densities (>80%)

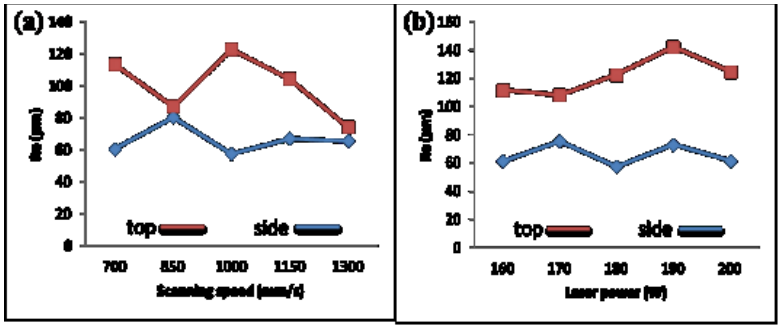

Fig. 8. Effect of the laser scanning speed and laser power on surface roughness: (a) laser scanning speed; (b) laser power

were obtained when the energy density was larger than 52J/mm^3. There was an increase in relative density from 78.81% to 85.6% when laser power increased from 46.2J/mm^3 to 85.7J/mm^3. A lot of un-melted particles and porosities were observed in samples because the incomplete melting of the powders due to insufficient laser energy density. The relative density decreased from 85.6% to 78.8% when the laser scanning speed was increased from 700mm/s to 1,300mm/s. There was an increase in relative density from 80.46% to 83.94% when the laser power increased from 160W to 180W at a constant scanning speed of 1,000 mm/s. This research indicates that SLM technology is suitable for the manufacture of vanadium alloy parts and there are repeat abilities in the manufacturing of vanadium alloy parts.

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