The effect of laser power and scanning speed on forming structure in selective laser melting process

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Abstract

With the continuous development of ship technology, the usage environment of some parts has changed, with higher requirements for materials and preparation technology being put forward. Some traditional structural materials have not meet the actual working conditions of ships, which necessitates development of new materials and research on their preparation technology. Owing to its high strength and stable mechanical properties at high temperature, molybdenum base alloy is expected to replace nickel base alloy and aluminum base alloy the primary structural material in the development of ships. Under the conventional method, the impurity elements is quite complex and there are limitations in the shape of the formed parts. This experiment uses spherical pure molybdenum powder as raw material. The effects of laser power, powder thickness, scanning speed and scanning distance on the microstructure of formed parts during selective laser melting process were studied and the optimum process parameters were determined. Laser power and scanning speed can seriously affect the quality of the forming parts. In this experiment, by comparing the density and internal holes of the forming parts under different process parameters, the best preparation process for the forming parts was determined: laser power 325 watts, scanning speed 400 mm s⁻¹, powder thickness 30 μm, scanning distance 40 μm. Meanwhile, the forming workpiece density is the largest, up to 94.92%.

1. Introduction

Molybdenum is a rare metal with a high melting point. Molybdenum base alloy has high strength and stable mechanical properties at high temperature, and is widely used in metal pressure processing, metallurgy, machinery, aerospace military industry and nuclear industry. The development of selective laser melting technology provides a new way to prepare high performance molybdenum base alloys. This method can be used to form the workpiece of complex structures, and may be a reliable in the preparation of ship structural materials. Therefore, research on selective laser melting technology of molybdenum base alloy is of great significance [1, 2].

Selective laser melting forming technology is based on the metal powder melting and deposition manufacturing process, and does not involve mechanical pressure, so it is easy for the forming parts to have gaps and defects, resulting in reduced density of the formed parts. The formation of these defects is closely related to temperature gradient, surface tension gradient, thermal capillarity and bubble movement during the formation of molten metal. The interaction of these unsteady processes leads to the flow of molten metal and is closely related to spherification behavior [3–7]. The formation of pores will greatly reduce the mechanical properties of the formed parts and negatively affect their practicability [8].

At present, there are typical problems related to laser melting technology in selected fields at home and abroad [9–14]. Such problems can be summarized as follows: the density of formed parts is not high, the
dimensional accuracy of formed parts is not high, the surface of formed parts is rough, the number of molded parts is large, the performance of formed parts is unstable, etc [9, 15, 16]. These problems are inseparable from the control of laser melting formation process, such as powder properties, substrate materials, energy input and melting channel circulation rate. To solve these problems, it is necessary to have a deeper understanding of the laser melting formation process, which will also involve deeper exploration of material science.

2. Experimental procedure

The shape metal powders used in this experiment are spherical molybdenum powder and atomized spherical cobalt powder prepared by Wuxi Xindehuarui Powder New Material Technology Co., Ltd., with particle sizes ranging from 13 μm to 53 μm. The morphology and particle size distribution of the spherical pure molybdenum powder are shown in figures 1 and 2, respectively. As can be seen from the figure, the particle size of the metal powder used in this experiment has a wide distribution range, with an average particle size of 35.8 μm, which is close to the mass median aerodynamic diameter of powder material required by the AFS-M260 device.

The size of the forming parts in this experiment were 10 mm × 10 mm × 10 mm. The scanning strategy was to rotate 67° layer by layer [17–19], powder thickness was 30 μm [20], scanning spacing was 40 μm [21, 22]. After the selected laser melting process, the DK7745 edM CNC cutting machine was used to cut the forming parts from the forming substrate. After mechanical grinding and polishing, the forming parts were dried and preserved. Then, 2.6 g K₃Fe(CN)₆ and 2.3 g NaOH were weighed and dissolved in 20 ml distilled water to configure the corrosion solution. After etching for 1 min, the solution was washed with distilled water. After polishing, the surface lost luster, and the solution was washed with alcohol and blow-dried for preservation.
PME3 metallographic microscope and Quanta 200 environmental scanning electron microscope were used to observe the metallographic structure and high magnification structure of different formed parts.

3. Results and analysis

3.1. Influence of the laser power on the forming process

A high energy laser beam with different laser power density will cause different physical changes on metal surface. When the laser vaporizes the metal to produce weakly-ionized plasma, the rate at which the metal powder absorbs laser energy increases. When the laser power is too high, strong gasification of metal produces plasma with high ionization degree, and greatly reduces the absorption rate of laser energy by the metal powder. If the laser power density is too low during laser melting formation in the selected area, the powder layer may not melt completely or penetrate the pre-cured layer, resulting in degraded performance of the formed portion. If the laser power density is too high, a laser-shielding plasma is generated, which hinders absorption of energy by the metal powder and reduces the performance of the molded parts [23–25].

Figure 3 is the macro morphology and triple magnification of the forming parts under different laser powers. In this case, the scanning speed is 400 mm s⁻¹. As can be seen from the figure, when the laser power is 250 watts, the shape of the sample is relatively regular, but there are a lot of holes on the surface, and the roughness is 34 μm. When the laser power is increased to 275 watts, the forming surface becomes flat, the number of holes and the roughness are improved obviously, and the roughness is 25 μm. As the laser power continues to increase, the shape becomes clearer, with no deeper holes and roughness as low as 19 μm. The sample has the best appearance quality at this time. When the laser power continues to increase to 375 watts, the shape becomes irregular, the forming surface is no longer flat, the laser printing boundary is obvious, and the roughness changes to 56 μm. When the laser power is 400 watts, the edge warping of the forming parts is serious. The warping deformation will hinder the operation of the spreading roller, resulting in uneven paving and uneven formation. At this time, the roughness of the forming surface is the worst, reaching the millimeter level.

The increase in laser power increases thermal stress inside the material [26, 27]. As the molten metal liquid cools and solidifies, thermal stress in the material is converted to residual stress, which is stored in the solidified layer. As the forming process continues, the residual stress increases gradually. When the residual stress exceeds the yield strength of the material, the forming part will be deformed. Meanwhile, when a laser beam with too much power acts on the surface of the powder layer, the material will be strongly vaporized. The creation of metallic vapor increases recoil pressure in the molten pool, which squeezes a portion of the molten metal. Small dispersed droplets are formed in the pool and unmelted metal powder is removed from the pool. This splashing phenomenon is also an important reason for the uneven surface of molded parts [28–31].

Figure 4 shows the metallographic structure of pure molybdenum forming parts under different laser powers. As can be seen from the figure, when the laser power is 250 watts, there are a lot of voids inside the formed part and the defect size is also large. When the laser power is too low, part of the metal powder absorbs the laser energy and melts gradually, but part of the metal powder does not melt. As the fiber laser moves rapidly, the molten pool gradually cools and solidifies, and the unmelted area forms a larger defect. When the laser power is increased to 275 watts, the internal porosity of the formed part reduces. It can also be seen that there are still large defects in the formed part, indicating that the laser power is still not enough to completely melt the metal powder. When the laser power is further increased to 300 watts, the internal pores of the formed part are further reduced, and the defects are not of large size. When the laser power is increased to 325 watts, the microstructure of the formed part does not change.
Figure 5 shows the morphology of melting trajectories of pure molybdenum formation under different laser powers observed under a scanning electron microscope. As shown in figure 5, the variation of laser power has great influence on the morphology of the partially melted section, while the morphology of the melting channel can reflect the motion behavior of the light spot to a certain extent. When the laser power is 250 watts, the formed part shows no continuous melting path and contains some spherical particles of small size. This is because the energy input into the powder layer at this time is not enough to completely melt the metal powder; as the laser moves, scattered molten pools are formed [32]. When laser power increases to 275 watts, the number of spherical particles in the forming part is significantly reduced, and a continuous melting path can be observed, but the height of the melting path is low, making it less obvious. When laser power is increased to 300 watts, the height of the melting tunnel increases and the melting channel becomes obvious. At this point, the surface of the melting channel takes the the shape of fish scales, and the boundary of the melting channel is roughly parabolic. When the laser power is further increased to 325 watts, the melting channel is continuous, the change of height direction is not obvious, and the fish-scale shape of the melting channel becomes more obvious.

3.2. The effect of scanning speed on the forming process

The scanning speed has great influence on the forming quality of the workpiece. The scanning speed determines by the energy inputted from the laser into the powder layer. The lower the scanning speed, the longer the laser time on the metal powder per unit area and the larger the energy inputted. At this point, the metal powder has enough time to melt and form a molten pool. Additionally, the metal powder around the molten pool is drawn into the inside of the molten pool under the action of capillary force, thus the molten pool is filled and the density of the formed part increases [33–36]. When the scanning speed is low, the forming time of workpiece increases greatly, and the forming cycle of the workpiece extends obviously. If the scanning speed is too high, the laser time on the metal powder becomes shorter, meaning the powder will not be completely melted and solidified, which will reduce the density of the formed part.

In this experiment, the effects of laser power and scanning speed on the density of the forming workpiece were investigated by orthogonal experiment. The laser power was set to 200 watts, 225 watts, 250 watts, 275 watts, 300 watts, 325 watts and 350 watts. The scanning speed was set to 400 mm s\(^{-1}\), 60 mm s\(^{-1}\), 800 mm s\(^{-1}\) and 1000 mm s\(^{-1}\), respectively. Other process parameters remained unchanged, the scanning spacing was 60 μm, the powder thickness was 30 μm, and the scanning strategy was layer-by-layer rotation 67° scanning strategy. The forming base material was pure molybdenum base material, and the forming chamber was filled with 99.9% argon gas to ensure that the oxygen content in the forming chamber was less than 1000 ppm to meet the requirements of the device. After processing, a steel wire knife was used to separate the formed parts from the
forming base material, and Archimedes drainage method was used to measure the density of the formed parts. The densities of the formed parts under different process parameters are shown in table 1.

In order to more intuitively reflect the influence of laser power and scanning speed on the density of formed parts and optimize the forming process, the above data are drawn into broken line statistics, as shown in figure 6.

Figure 7 shows the morphology of the melting track of pure molybdenum formed parts under different scanning speeds. As can be seen from the figure, laser power and scanning speed significantly affect the density of the formed part. At a constant scanning speed, the laser power was increased appropriately and the molded products tended to be compact. Under different scanning speeds set in this experiment, the laser power was set to 325 watts to obtain the densest formed parts. As the laser power was increased further, the density of the formed part began to decrease. At the same scanning speed, when the laser power is set at 350 watts, the density of the formed part decreases significantly. Under the condition of constant laser power, the scanning speed was set to 400 mm s$^{-1}$ or 600 mm s$^{-1}$ to promote the densification of the forming parts. The density of the formed part was lowest when the scanning speed was set to 1000 mm s$^{-1}$. Among all the technological parameters set in

| Scan speed (mm/s) | Laser power (w) | 200 | 225 | 250 | 275 | 300 | 325 | 350 |
|------------------|----------------|-----|-----|-----|-----|-----|-----|-----|
| 400              | 82.57%         | 83.11% | 88.36% | 90.08% | 92.05% | 94.92% | 91.32% |
| 600              | 78.19%         | 84.42% | 85.25% | 91.84% | 91.10% | 92.32% | 89.96% |
| 800              | 76.30%         | 83.64% | 83.32% | 88.64% | 90.21% | 91.48% | 88.42% |
| 1000             | 75.09%         | 81.25% | 82.21% | 83.31% | 83.42% | 84.56% | 82.37% |

Figure 5. Melting track morphology of pure molybdenum formed parts under different laser powers (a) 250 w; (b) 275 w; (c) 300 w; (d) 325 w.
Figure 6. Effects of laser power and scanning speed on the density of formed parts.

Figure 7. Melting track morphology of pure molybdenum formed parts under different scanning speeds (a) 400 mm/s; (b) 600 mm/s; (c) 800 mm/s; (d) 1000 mm/s.
this experiment, the density of the formed parts was highest at 94.92%, when laser power was set to 325 watts, and the scanning speed was set to 400 mm s\(^{-1}\).

4. Discussion

4.1. Formation mechanism of fish scales in the melting channel

The fish-scale shape of the melting channel is related to the solidification behavior of the molten pool, that is, the temperature change in the whole molten pool during the forming process\([37, 38]\). The energy distribution of the fiber laser is approximately Gauss. The energy near the light spot center is high and the temperature of the molten pool is high at this area, while the energy far from the light spot center is low and the temperature of the molten pool is low. During the forming process, the high-energy laser beam moves along the scanning direction and melts the metal powder at different parts of the specific trajectory, forming molten pools with complex temperature gradients. Figure 8 is a schematic diagram of light spot movement during the forming process.

In the figure, \(x\) is the scanning direction, that is, the moving direction of the light spot; \(y\) is the width direction of the melting passage; point \(O_1\) is the current position of the light spot; point \(O_2\) is the position of the light spot after time \(t\). If the scanning speed of laser is \(v\), the distance between two points of \(O_1\) and \(O_2\) can be expressed as \(vt\). The radius of the melting region of metal powder under the action of laser is \(R\), and the size of this region is different from the size of the light spot. Therefore, circle \(O_1\) represents the region where the molten metal powder at the current moment, while the circle \(O_2\) represents the region where the molten metal powder after time \(t\). The intersection points of the boundaries of the two regions are represented as \(P_1\) and \(P_2\) respectively.

The areas of circles \(O_1\) and \(O_2\) can be expressed as:

\[
(x - R)^2 + y^2 \leq R^2
\]
\[
(x - R - vt)^2 + y^2 \leq R^2
\]

The coordinates \(P_1\) and \(P_2\) of the intersection of circles \(O_1\) and \(O_2\) can be derived as:

\[
x = R + \frac{vt}{2}, \quad y = \pm \sqrt{R^2 - \left(\frac{vt}{2}\right)^2}
\]

When the laser is in the current position, the metal powder in the light spot \(O_1\) melts to form a molten pool with high temperature near \(O_1\) and low temperature away from \(O_1\). As the process progresses, the spot moves and the temperature gradients within the molten pool become extremely complex. After time \(t\), the light spot moves to \(O_2\), and the temperature of the molten pool far away from \(O_2\) begins to drop, with the temperature of the shaded area in the figure reaches the solidification temperature firstly, and solidification occurs. The boundary of this region is approximately parabolic, leading to the formation of fish-scale shapes on the surface of the melting channel.

Taking the boundary of the shaded region as a parabola, two parabolic equations passing through the origin \(O\), \(P_1\) and \(P_2\) can be obtained:
The fish scale morphology of the melting channel is determined by the radius $R$ of the molten region of metal powder under the action of laser, the scanning speed $v$, and the time required for the complete solidification of the shadow region. Time $t$ is determined by the melting point of the metal powder and temperature changes within the region $[39]$. Therefore, $t$ is also a variable corresponding to different forming processes.

4.2. Forming member densification mechanism

It can be seen from figure 7 that the change of scanning speed has great influence on the morphology of the melting passage of forming parts. When the scanning speed is set to $400 \text{ mm s}^{-1}$ and $600 \text{ mm s}^{-1}$, the melting channel of the forming part is clear and continuous. When the scanning speed is set to $800 \text{ mm s}^{-1}$ and $1000 \text{ mm s}^{-1}$, the forming part does not have continuous melting channel, which is related to the energy density inside the input powder layer. When the scanning speed is set to $400 \text{ mm s}^{-1}$, there are very few metal spheres in the tissue of the forming parts. With the increase of scanning speed to $600 \text{ mm s}^{-1}$, the spheroidization tendency increases and a large number of metal spheres appear in the tissue of the forming parts. With the further increase of scanning speed, spherification behavior becomes more and more obvious. The increase of scanning speed reduces the energy density in the input powder layer, which will lower the temperature of the molten pool formed after the melting of metal powder and reduce the content of molten liquid metal $[40]$. On the one hand, the lower molten pool temperature increases the viscosity of liquid metal, making the fluidity worse and forming spheroidization easily.

On the other hand, as the scanning speed increases, the temperature of molten pool becomes lower, leading to an increase in the cooling rate. And the liquid metal has solidified without diffusion on the surface of the previous forming layer, which also leads to the increase of spheroidization tendency.

It can be found that the diffusion time and solidification time of melt determine the tendency of the spheroidization during the forming process to a certain extent. If the melt is approximated as a sphere, the diffusion time of the melt can be calculated by the following formula $[41]$:

$$\tau = \sqrt[3]{\frac{\rho_m a^3}{\sigma}}$$

Where $\rho_m$ is the density of liquid molybdenum, $a$ is the radius of spherical droplet, and $\sigma$ is the surface tension of liquid molybdenum.

The solidification time $t$ of the melt can be calculated by the following equation $[42]$:

$$t = \frac{2a^2}{3\alpha} \ln \left( \frac{T_0 - T_f}{T_f - T_i} \right)$$

Where $\alpha$ is the thermal diffusion coefficient of liquid molybdenum, $T_0$ is the temperature of liquid molybdenum, $T_i$ is the temperature of forming substrate, $T_f$ is the solidification temperature of molybdenum metal.

The spreading time and solidification time of melt can be approximately calculated by the above two formulas. However, the diffusion and solidification behavior of the melt are quite complicated due to the influence of laser energy and heat dissipation conditions during the forming process. There is a certain difference between the theoretical values and experimental values.

It is certain that in the actual process, if the diffusion time $\tau^*$ of the actual melt is much larger than the solidification time $t^*$ of the actual melt, spheroidization behavior tends to be more obvious during the forming process.

5. Conclusions

1. If the laser power density is too low, the powder layer will not melt completely or the pre-solidified layer will not be penetrated. At this time, the appearance quality and roughness of the forming parts are low. When the laser power density is too high, the rapid increase of thermal stress in the material will lead to the deformation of the forming parts. At the same time, too high laser power will increase the number of sputtering, make the forming parts have defects, and thus reduce the performance of the forming parts.

2. The action time of laser on metal powder in unit time is inversely proportional to the scanning speed. When the scanning speed is low, the laser has enough time to act on the metal powder per unit area and enough energy to make the metal powder have enough time to melt and form a molten pool. The metal powder around the molten pool is drawn into the molten pool under the action of capillary force, so that the molten
pool is filled and the density of the forming parts is improved. The increase of scanning speed will reduce the energy density inside the powder layer, make the molten pool temperature lower, increase the viscosity of liquid metal, reduce the fluidity, and easy to form spheroidization. In addition, with the increase of scanning speed, the molten pool temperature decreases and the cooling rate increases. The liquid metal has solidified without spreading on the surface of the previous forming layer, which also leads to the increase of spheroidization tendency.

3. In this experiment, by comparing the surface quality, internal defects and density of the forming parts under different laser power and scanning speed, the optimal preparation process of forming parts is determined as follows: laser power 325 watts, scanning speed 400 mm s
-1, powder thickness 30 μm, scanning distance 40 μm. Under this parameter, the forming workpiece density is 94.92%.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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