Research on Manufacturing Technology of Thin-walled Parts of Fe105 metal Based on Laser Cladding

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Abstract. According to some working conditions of thin-walled parts, Fe105 iron-based alloy powder is used to print parts based on laser cladding. Laser cladding, also called 3D Print, is the last manufacturing method in world. The test method of single factor experiment and orthogonal experiment is used to find the best parameters of powder feed rate, laser power, scanning speed and gas flow rate. The research is based on the laser cladding, using advanced equipment, such as, OM, SEM, Micro-hardness, to find out the best parameters of laser machine. Also, by the equipment, the morphology and characteristic of thin-walled parts were studied.

1. Introduction
Laser cladding technology is also known as 3D printing technology, which is the new material processing and manufacturing technology[1], its working principle is that using high energy density of laser beam exposure on the substrate to simultaneously send alloy powder. Powder and substrate surface clad together. Thin-walled parts are widely used in industry and life[2], but in the process of machining, because of the fixed workpiece and forging processing problems, leading to poor shape-accuracy of parts. The property of Fe105 metal powder, such as, large hardness, good wear resistance, low cost, is the reason why it is chosen to be the raw material. The research will adopt the method of laser cladding and use Fe105 alloy power. Single-channel multilayer forming experiment[3] was carried out. The research studied optimization and performance on the process.

2. Experiment and analyse
For this experiment, firstly, single factor experiment should be done to find the scope of the best parameters, after using orthogonal experiment to make sure the parameters.

2.1 Materials and evaluation parameters
Substrate materials is #45 steel and alloy powder is Fe105 metal, the components of it is shown in the table 1. Fe105 metal alloy powder as cladding material, because of its hardness and the ability of cladding layer to resist anti-cracking performance. Antioxidant ability of Fe105 metal is strong.

Laser cladding system adopted in the experiment is constituted by KUKA ZH30/60 robot, powder feeding pump, laser transmitter, optical maser, laser control system and experiment platform.
Table 1. Components of Fe105 alloy powder

| Components | C   | Cr  | Si  | Mo  | Ni  | Mn  | B  |
|------------|-----|-----|-----|-----|-----|-----|----|
| Mass Fraction | 1.5 | 4.5 | 1.3 | 1.5 | 12  | 1   | 2.8|

Experiment for the research is single-channel monolayer experiment by laser system. The important influence factors of laser cladding mainly includes scanning speed, laser power, powder feed rate, gas flow rate[4].

For Z axis lifting capacity and laser zoom, because of single-channel monolayer experiment cannot study it and the laser system cannot change zoom, the research is incapable to study it. Single factor experiment using specific data are shown in table 2.

Table 2. The range of single factor experiment

| Value range | Average |
|-------------|---------|
| Laser power (W) | 350/380/410/440/470/500/530 | 440 |
| Scanning speed (mm/s) | 4/4.5/5.5/6.5/7 | 5.5 |
| Powder feed rate (r/min) | 0.3/0.4/0.5/0.6/0.7/0.8/0.9 | 0.6 |
| Gas flow rate (L/h) | 9/11/13/15/17/19/21 | 15 |

Single-channel monolayer experiment evolution parameters mainly include: the shape coefficient of single-channel cladding layer and cladding layer dilution rate D[5-6].

The shape coefficient calculation formula is as follow:

\[\zeta = \frac{b}{H}\] (1)

H is the height of the cladding layer and b is the width of the cladding layer. The shape coefficient is the ratio of width to height of cladding layer. It is generally believed that when the ratio is 2 or less than 2, the collapsed cladding layer phenomenon may occur. When the ratio is more than 2, the effect of the cladding layer is stable, which can print valuable micro thin-walled parts. But when the \(\zeta\) is much larger than 2, the cladding remelting area will expand, which is harmful to the cladding layer.

The dilution rate D calculation formula is as follow:

\[D = \frac{S_2}{S_1 + S_2}\] (2)

For the formula, S1 is the meaning of the area on vertical direction along the cross-sectional face of laser cladding layer. S2 is the meaning of the area on vertical direction along the cross-sectional face of substrate material. Because the formula is the calculation of the area, the formula can be converted into the following form:

\[D = \frac{h}{h + H}\] (3)

Equation (3) can be simplified as the following form:

\[D = \frac{h}{h + H}\] (4)

h is the height of the miscibility area of substrate.

Normally, dilution rate D should be stable within a certain range, if the dilution rate D is too small, metal on the surface of the molten pool is too small to be strong and it’s harmful to cladding. But if the dilution rate D is too large, it will cause the thickness of the cladding layer. And if the laser energy is too high, it’s easy to cause the surface cracking, deformation and collapse. So the dilution rate should be in the safety range[7].

2.2 Results of experiment

2.2.1 Single factor experiment

For the single factor experiment, the research focus on the four parameters points of laser cladding: scanning speed \(V_s\), laser power \(P\), powder feed rate \(V_f\) and gas flow rate \(G\). With laser cladding system, the results of the single factor experiment are shown in table3, table4, table5 and table6.
Table 3. Single factor experimental results of laser power

| P (w) | V_d(mm/s) | V_f(r/min) | G(L/h) | ζ  |
|-------|------------|-------------|--------|----|
| 1     | 320        |             |        | 2.836 |
| 2     | 350        |             |        | 2.322 |
| 3     | 380        |             |        | 2.289 |
| 4     | 410        | 5.5         | 0.6    | 15  | 2.367 |
| 5     | 440        |             |        | 2.352 |
| 6     | 470        |             |        | 3.143 |
| 7     | 500        |             |        | 3.208 |

The data in the table 3 show that P=470W and P=500W is too large for the experiment. The shape coefficient is much larger than others. And when P=320, P=350, P=380 laser power is too small, the substrate materials cannot completely melt, as well as, irregular feature of vertical direction along the cross-sectional face of laser cladding layer is obvious. Sticky powder phenomenon is also obvious. And it cannot reach the purpose of the laser cladding. So at last, the range of laser power are P=410W, P=440W. And another parameter is the average of them, P=425W.

Table 4. Single factor experimental results of scanning speed

| P (w) | V_d(mm/s) | V_f(r/min) | G(L/h) | ζ  |
|-------|------------|-------------|--------|----|
| 1     | 4          |             |        | 1.658 |
| 2     | 4.5        |             |        | 1.873 |
| 3     | 5          |             |        | 2.412 |
| 4     | 410        | 5.5         | 0.6    | 15  | 2.367 |
| 5     | 6          |             |        | 2.262 |
| 6     | 6.5        |             |        | 2.464 |
| 7     | 7          |             |        | 2.541 |

In the case of other parameters constant, faster scanning speed will reduce the time of the powder stay on the substrate materials, because of that, it can also reduce the balling phenomenon. But when the scanning speed is too fast to make metal melt, the molten pool will be discontinuous.

The data in the table 4 show that shape coefficient is less than 2 when V_s=4, and V_s=4.5. Because the scanning speed is slow, leading to metal powder stack on the surface of substrate. The effect of the cladding is deteriorate. But when the V_s=7, V_s=6.5, the scanning speed is too fast, the powder cannot melt completely, sticky powder phenomenon is obvious. Finally, V_s=5, V_s=5.5 compared with V_s=6 that had the better cladding effect. The range of scanning speed are V_s=5, V_s=5.5, and another one is the average of them, V_s=5.25.

Table 5. Single factor experimental results of powder feed rate

| P (w) | V_d(mm/s) | V_f(r/min) | G(L/h) | ζ  |
|-------|------------|-------------|--------|----|
| 1     | 0.3        |             |        | 2.430 |
| 2     | 0.4        |             |        | 2.585 |
| 3     | 0.5        |             |        | 2.207 |
| 4     | 410        | 5.5         | 0.6    | 15  | 2.367 |
| 5     | 0.7        |             |        | 2.196 |
| 6     | 0.8        |             |        | 2.603 |
| 7     | 0.9        |             |        | 2.372 |

Powder feed rate is important for the effect of laser cladding. With the large powder feed rate, powder is too much for the laser, powder cannot absorb the energy of the laser, it cannot melt completely and result of it is cladding layer become worse. However, with the small rate, powder feed system can not determine the output. The powder feed rate of the research isn’t certain.

The data in table 5 show that when V_f=0.7, V_f=0.8, V_f=0.9, the rate is so large that some powder cannot melt, the phenomenon of sticky powder is obvious. When V_f=0.3, V_f=0.4, the shape of the cladding layer cannot be guaranteed. The effect of cladding layer is terrible. Because of that, the range of powder feed rate are V_f=0.5, V_f=0.6, and another one is the average, V_f=0.55.
Table 6. Single factor experimental results of gas flow rate

| P (w) | V_d (mm/s) | V_f (r/min) | G (L/h) | \( \zeta \) |
|-------|------------|-------------|---------|--------|
| 1     | 9          | 2.432       |         |        |
| 2     | 11         | 1.965       |         |        |
| 3     | 13         | 2.128       |         |        |
| 4     | 410        | 5.5         | 0.6     | 15     |
| 5     | 17         | 2.415       |         |        |
| 6     | 19         | 2.725       |         |        |
| 7     | 21         | 3.157       |         |        |

Shielding gas protect the cladding layer so that it can’t be oxidized under the condition of high temperature. But too large gas flow rate may affect the experiment. Because shielding gas may blow away the metal powder and change the landing site of metal powder on the surface of substrate[8].

The data in table 5 show when the G=11, the shape coefficient is less than 2, so it is abandoned. When the G=19 and G=21, the shielding gas flow rate is too large. It may blow away the metal powder and some powder cannot absorb the energy of the laser, because of that, powder can’t be stacked on the surface and the shape coefficient much larger than others. So at last, the range of shielding gas flow rate are G=13 and G=15. Another one is average of them, G=14.

2.2.2 Orthogonal experiment

By single factor experiment, research find that cladding layer is effected by these factors, the laser power, scanning speed, powder feeding speed and shielding gas flow rate. Each influence factors had their own way to affect the text. Research selected the three horizontal reference values of each parameters, for that select the optimal solution of laser cladding by Fe105 metal powder.

Research adopt the orthogonal experiment by random grouping, the test is four factors and three levels orthogonal experiment grouping conditions and the results are shown in table 7.

Table 7. Orthogonal experiment table

| P(W) | V_d (mm/s) | V_f (r/min) | G (L/h) | \( \zeta \) |
|------|------------|-------------|---------|--------|
| 1    | 410        | 5.00        | 0.50    | 15     |
| 2    | 410        | 5.25        | 0.55    | 14     |
| 3    | 410        | 5.50        | 0.60    | 13     |
| 4    | 425        | 5.00        | 0.50    | 14     |
| 5    | 425        | 5.25        | 0.55    | 13     |
| 6    | 425        | 5.50        | 0.60    | 15     |
| 7    | 440        | 5.00        | 0.55    | 15     |
| 8    | 440        | 5.25        | 0.60    | 14     |
| 9    | 440        | 5.50        | 0.50    | 13     |
| 10   | 410        | 5.00        | 0.50    | 13     |
| 11   | 410        | 5.25        | 0.50    | 15     |
| 12   | 410        | 5.50        | 0.55    | 14     |
| 13   | 425        | 5.00        | 0.55    | 13     |
| 14   | 425        | 5.25        | 0.60    | 15     |
| 15   | 425        | 5.50        | 0.50    | 14     |
| 16   | 440        | 5.00        | 0.60    | 14     |
| 17   | 440        | 5.25        | 0.50    | 13     |
| 18   | 440        | 5.50        | 0.55    | 15     |

In theory, when laser cladding print thin-walled part which have radian, the shape coefficient of the cladding layer must more than 3. If the ratio less than 3, the thin-walled parts prone to collapse and bend. But when the shape coefficient is too large, the width of the cladding layer is too thick which will cause the height of cladding layer is insufficient that will affect the printing effect of thin-walled parts[9]. In the table 7, group 1, 4, 6, 7, 10, 14, 16, 18 meet the requirements, but the group 18 is large
than others and group 10 and 14 just a little more than 3, so the research rule out them and continue to study group 1, group 4, group 6, group 7, group 16.

|   | 1   | 4   | 6   | 7   | 16  |
|---|-----|-----|-----|-----|-----|
| D | 0.418 | 0.323 | 0.369 | 0.381 | 0.4061 |

Dilution rate is important for the cladding layer. Due to the effect of high temperature from laser, in the process of cladding, laser can make the cladding layer and substrate a certain extent dilution, and this phenomenon is inevitable. Within the scope of the dilution ratio, the ratio is smaller, the result of the test will be better. Dilution ratio ensure that the performance of cladding layer. But the dilution rate can’t be too small. For that dilution rate will lead to the cladding layer and substrate could not form a combination on the surface of substrate.

Cladding layer dilution rate of five groups are shown in the table 8. All of ratio were among from 3 to 5 and dilution rate meet the basic requirements. Group 4 had the smallest dilution rate so the optimal solution is group 4 with P=425W, V_s=5mm/s, V_f=0.50r/min, G=14L/h.

3. Organizational analysis of thin-walled parts

The research use the optimal solution to print a micro thin-walled parts. The parts was processed and it was analysed by electron microscope.

It can be seen in Fig1(a) that at the bottom of the cladding layer, a good metallurgical bonding is formed between cladding layer and the substrate. And there is a clear structural transformation at the bonding interface. There is a thin planar crystal transition structure between the cladding layer and the substrate. Then, the columnar crystal at the bottom of the cladding layer grows epitaxially along the substrate, inversing heat flow direction and extending to the cladding layer.

As the growth distance increases, the crystal size gradually changes from a single thick columnar crystal to a small cross-dendrite. In the middle of the cladding layer, as shown in Fig1(b), the cladding layer is mainly composed of crystallized oriented cross-dendrites and tiny equiaxed crystals. At the top of the cladding layer, the structure is mainly composed of denser and smaller equiaxed crystals, as shown in Fig1(c). It also can be seen the microstructures of cladding surface in Fig1(d)(e)(f).

By observing the microstructure change of the cladding layer from the bottom to the top, the overall microstructure transformation of the cladding layer is homogeneous, the microstructure is dense and small. There is no crystal structure which is abnormal thick or throughout the crystallization zone. And there is no microcracks, blowholes and other defects inside the cladding layer. The cladding layer shows good microstructure characteristics of laser cladding and orientated solidification and excellent forming quality.
Figure 1. Microstructures of cladding: (a) substrate and bonding interface region (b) intermediate region (c) top region
Microstructures of cladding surface (d) substrate and bonding interface region (e) intermediate region (f) top region

4. Conclusion
The research is based on the laser cladding to print a micro thin-walled parts by Fe105 metal powder. In the process of the experiment, the research adopted single factor and the orthogonal test to find out the optimal solution of the Fe105 metal powder.

The experiment force on four parameters: scanning speed ($V_s$), laser power ($P$), powder feed rate ($V_f$), gas flow rate ($G$). And by the single factor test, the study found the range of the optimal parameters by the shape coefficient of single-channel cladding layer and cladding layer dilution rate. Within the range, the study does the orthogonal experiment. The study analyse the data by the state of the cladding layer. At the end of experiment, the study find that when $P=425$W, $V_s=5$mm/s, $V_f=0.50$r/min, $G=14$L/h, the state of the cladding layer is good and also the shape coefficient and dilution rate meet the requirements.

The study also used the electron microscope to analyse the microstructures of cladding. The study found there is no micro-cracks, blowholes and other defects inside the cladding layer.

Acknowledgment
This work was supported by the National Ministry of Industry and Information major special projects research fund (201675514).

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