Process parameters optimization of single-track laser cladding for 45 steel gear remanufacturing

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Abstract. In order to research the optimal combination of process parameters for the remanufacturing of 45 steel gear with RCF104 alloy powder, three-factor and five-level orthogonal experiments of laser power, scanning speed and powder feeding speed were carried out on 45 steel substrate. The best process parameters combination was selected by considering the shape coefficient of the cladding layer, dilution rate, cladding width and cladding height. The microstructure of the cladding layer was analyzed, the horizontal and vertical microhardness of the cladding layer was measured. The results show that the optimal combination of process parameters was laser power 448 W, scanning speed 6 mm/s, powder feeding speed 9.0369 g/min. The analysis of variance shows that the laser power and scanning speed were the main factors influencing the cladding width and the scanning speed had a significant influence on the cladding height and shape coefficient. The microstructure analysis of cladding layer shows that planar crystals, cellular crystals, columnar crystals, dendrites and equiaxed crystals changed gradually from bottom to top. The average microhardness of the cladding layer was 672.2 HV, which was 3.08 times of the matrix hardness.

1. Introduction
Laser cladding technology is a technology that uses laser as heat source to melt and solidify metal powder rapidly. In recent years, laser cladding technology has been widely used in the field of remanufacturing, such as roller, transmission shaft, gear, sprocket and other parts, which is full of great economic value. 45 steel gear is an important transmission part, which maybe occurs broken teeth, tooth surface pitting corrosion, tooth surface wear and other failures [10]. As single laser cladding is the basis for the remanufacturing, so it is necessary to carry out the optimization of single process parameters. Hua ming Liu [4] researched the effects of laser power, powder feeding speed and scanning speed on the width, height and dilution rate of cladding layer through taguchi method, and obtained the optimal process parameters. Then they repaired the sprocket with the optimized process parameters. Yang Liu [5] researched the effects of laser power, scanning speed, powder feeding speed and protective gas flow on the single track macroscopic morphology, melting height, melting width...
and melting depth, and optimized the optimum combination of technological parameters based on the relative density of the sediments. Suha k. Shihab [6] designed orthogonal experiments to study the influence of process parameters on the geometric morphology of cladding layer, and selected the optimal combination of process parameters by using the method of multi-objective parameter optimization. Yang Lin [9] used taguchi method to optimize the single-track process parameters of 313 alloy powder and analyzed the microstructure. Single track laser cladding is the basis of remanufacturing 45 steel gears. Good single-track process parameters are conducive to reducing defects such as porosity and cracks in remanufacturing parts, which can improve the quality of remanufactured parts. Therefore, it is significant to optimize single track process parameters and research the microstructure. In this paper, the orthogonal experiments were carried out, the optimum combination of process parameters was obtained through comprehensive analysis. The microstructure changes of cladding layer from bottom to top were analysed. The vertical and horizontal microhardness of single-track cladding layer was measured by microhardness tester.

2. Experiments

2.1. Equipment and materials

As shown in Figure 1, the laser cladding equipment consists of a six-degree-of-freedom KUKA robot, a coaxial laser cladding head, YLR-500 fiber laser generator (wave length 1020nm), a water-cooling machine, a gas-carrier single-cylinder single-hole coaxial powder feeder, a laser controller, a robot controller, and a water cooling machine and powder conveying pipeline. The substrate of this experiments choose 45 steel plates with size of 100×120×10mm (width × length × thickness). Before the experiments, the substrate was polished with sandpaper to remove the oxide layer on the surface of the substrate and then cleaned with alcohol. The powder is RCF104 iron base alloy powder, 100~270 mesh, the powder was dried at 120℃ for 4 h before the experiments.

The Element composition of 45 steel and RCF104 alloy powder is shown in Table 1 and Table 2.

| Elements | C     | Si     | Mn     | Cr     | S      | P      | Ni     | Cu     | Fe     |
|----------|-------|--------|--------|--------|--------|--------|--------|--------|--------|
| Proportion | 0.42–0.5 | 0.17–0.3 | 0.50–0.8 | <0.2  | <0.03  | <0.03  | <0.02  | <0.02  | Balance |

Figure 1. Diagram of experimental equipment
Table 2. Proportion of elements in RCF 104 alloy powder (mass%)

| Elements | C    | Mn   | Si   | B    | Cr   | Mo   | Ni   | Fe  |
|----------|------|------|------|------|------|------|------|-----|
| Proportion | 0.15~0.2 | ≤0.6 | 1.0~1.2 | 1.1~1.4 | 14.5~16.5 | 1.0~1.4 | 1.3~1.8 | Balance |

2.2. Selection of experimental process parameters

In the experiment, argon was used for both the shielding gas and powder sending gas, the flow rate of the powder gas is 8L/min, the flow rate of the protection gas is 15L/min, and the defocusing volume is 0 mm. Three-factor and five-level experiments were designed with the laser power, scanning speed and powder feeding speed. The levels of the three factors are shown in Table 3.

Table 3. Factors with their levels

| Factors | Level | P (w) | V (mm/s) | Vf (g/min) |
|---------|-------|-------|----------|-------------|
|         | 1     | 400   | 4.0      | 6.7772      |
|         | 2     | 412   | 4.5      | 7.5307      |
|         | 3     | 424   | 5.0      | 8.2838      |
|         | 4     | 436   | 5.5      | 9.0369      |
|         | 5     | 448   | 6.0      | 9.7600      |

2.3. Characterization of cladding layer section

As it can be seen from the schematic diagram of the cross section of the cladding layer, the heat affected zone (HAZ), the molten pool (MP) and the cladding layer are formed on the substrate after the interaction between laser, substrate and alloy powder [3]. The geometry shape of cladding layer is characterized by the width of the cladding layer (W), the height of the cladding layer (H), and the shape coefficient (η);

\[ \eta = \frac{W}{H} \] (1)

The depth of the molten pool is characterized by h. The larger h is, the better the bonding performance between the cladding layer and the substrate will be. The bonding performance is expressed by the dilution rate (λ);

\[ \lambda = \frac{h}{H + h} \] (2)

2.4. Cross section measurement and microstructure observation

Firstly, wire cutting equipment was used to cut the specimen, and the specimen width was 15mm. Then grinded it with sandpaper, the size of sandpaper is 240#, 400#, 600#, 800#, 1000#, 1200#, 1500#,
Then, the water-soluble diamond grinding paste of DNW1.5 was used for polishing for 30 min until there was no scratch on the surface of the specimen. Then the corrosion was carried out with ferric chloride corrosion solution and the microstructure was observed under the microscope, took pictures of the cladding section. The width, height and depth of cladding layer were measured and recorded in table 4.

3. Experiments analysis
The cross section characterization results of cladding layer are shown in Table 4. According to many research; When 2<\(\eta\)<3, the cladding layer section morphology is part of the semicircle or the circular arc, which is advantageous to the multi-track overlap between layers and can prevent defects of cladding layer, such as the internal cracks and porosity defects [2]. According to the shape coefficient, samples 4, 5, 10, 13, 14, 15, 20, 24, 25 were selected. When 5%<\(\lambda\)<25%, good metallurgical bonding is achieved between the cladding layer and the substrate. Samples 13, 15, 24, 25 were selected according to the dilution rate. According to the comprehensive analysis of samples 13, 15, 24 and 25, the dilution rate of sample 13 and 15 are relatively low, and the metallurgical bonding effect is worse than that of samples 24 and 25. The dilution rate of sample 24 is appropriate, but the shape coefficient is too small to facilitate multi-pass to layer lap forming. The melting width and melting height of sample 25 are suitable, the shape coefficient is large, the macroscopic morphology of the cladding layer is good, and the dilution rate is 17.74%, which can ensure the good metallurgical bonding performance between the cladding layer and the substrate as well as the subsequent cladding layer and layer. Therefore, the process parameters of sample 25 were selected as the forming process parameters [7].

4. Microstructure and microhardness

4.1. Microstructure of cladding layer
Figure 3 shows the microstructure of sample 25 at a magnification of 40 times from the bottom to the top. The analysis of Figure 3 (a) shows that the junction between cladding layer and substrate is a strip structure, which is a planar crystal, indicating that the cladding layer and substrate formed a good metallurgical combination. In Figure 3 (b), the microstructure gradually changed from thick columnar crystals to thick equiaxed crystals. Figure 3 (c) shows the coexistence region of columnar crystals, columnar dendritic crystals and equiaxed crystals, but the number of equiaxed crystals increased obviously. In Figure 3 (d), small and homogeneous isoaxial crystals were dominant, and some isoaxial crystals were a bit large. In summary, the microstructure evolved from planar crystals to columnar, cellular, dendrite, and equiaxed crystals from the bottom to the top gradually [8].

![Figure 3. Microstructure of cladding layer](image)

4.2. Microhardness measurement
Microhardness was measured by MH-6 microhardness tester, and microhardness is vickers’ microhardness. When measuring the transverse microhardness, 11 points were evenly taken from left
to right with a spacing of 80 um, as shown in Figure 4. 500gf was loaded and the load was maintained for 10s.

As it can be seen from Figure 5 (a), the cladding layer microhardness of -400–240um and 240um–400um is lower than that of -240–240um, which is closer to the symmetric center line. As it can be seen from the Figure 5, the minimum horizontal transverse microhardness of the single track cladding layer is 631.7HV and the maximum is 682.6HV. The lateral microhardness of the sample is basically symmetrical to the intermediate point 6 and the average horizontal microhardness is 663.9HV, which is 3.04 times of the substrate microhardness [1].

When measuring the hardness in the vertical direction, 8 points at 100um intervals from matrix to cladding layer were chosen to measure along the direction of the symmetrical center line of the cladding layer, the schematic diagram of measuring points is shown in Figure 4. 500gf was loaded, and the load was maintained for 10s.

As it can be seen from Figure 5 (b), the microhardness of the substrate is about 200 HV, which is the lowest compared with other points. The microhardness of the measuring point on the HAZ is higher than that of the cladding layer, which is mainly because the HAZ had undergone rapid heating and cooling, which is equivalent to quenching and the hardness had increased significantly. For the cladding layer, the hardness of 250-550um increases gradually, which is mainly due to the microstructure transformation of the cladding layer, such as planar crystal, cellular crystal, cellular dendritic crystal, columnar dendritic crystal, coarse isoaxial crystal and fine isoaxial crystal structure. The average hardness of the vertical cladding layer is 687.5HV, 3.14 times of the substrate. In conclusion, the average hardness in the vertical direction is greater than that in the horizontal direction. The average hardness of cladding layer is 672.2HV, which is 3.08 times of the substrate.

![Figure 4. Schematic diagram of microhardness measurement points of single cladding layer](image)

![Figure 5. Horizontal and vertical hardness of single cladding layer](image)
Table 4. Orthogonal test parameters and results

| NO. | $P$  | $V_s$ | $V_f$ | $W$  | $h$  | $\lambda$ | $H$  | $\eta$ |
|-----|------|-------|-------|------|------|-----------|------|-------|
| 1   | 400  | 4.0   | 0.45  | 1.246| 0.000| 0.0000    | 0.762| 1.635 |
| 2   | 400  | 4.5   | 0.50  | 1.241| 0.000| 0.0000    | 0.765| 1.622 |
| 3   | 400  | 5.0   | 0.55  | 1.278| 0.000| 0.0000    | 0.700| 1.825 |
| 4   | 400  | 5.5   | 0.60  | 1.215| 0.000| 0.0000    | 0.563| 2.158 |
| 5   | 400  | 6.0   | 0.65  | 1.233| 0.000| 0.0000    | 0.556| 2.217 |
| 6   | 412  | 4.0   | 0.50  | 1.534| 0.000| 0.0000    | 0.765| 1.622 |
| 7   | 412  | 4.5   | 0.55  | 1.247| 0.000| 0.0000    | 0.737| 1.691 |
| 8   | 412  | 5.0   | 0.60  | 1.283| 0.000| 0.0000    | 0.691| 1.856 |
| 9   | 412  | 5.5   | 0.65  | 1.278| 0.000| 0.0000    | 0.670| 1.904 |
| 10  | 412  | 6.0   | 0.45  | 1.236| 0.000| 0.0000    | 0.596| 2.073 |
| 11  | 424  | 4.0   | 0.55  | 1.311| 0.000| 0.0000    | 0.883| 1.484 |
| 12  | 424  | 4.5   | 0.60  | 1.287| 0.000| 0.0000    | 0.838| 1.535 |
| 13  | 424  | 5.0   | 0.65  | 1.498| 0.047| 0.0659    | 0.666| 2.249 |
| 14  | 424  | 5.5   | 0.45  | 1.285| 0.000| 0.0000    | 0.605| 2.123 |
| 15  | 424  | 6.0   | 0.50  | 1.245| 0.033| 0.0586    | 0.530| 2.349 |
| 16  | 436  | 4.0   | 0.60  | 1.368| 0.000| 0.0000    | 0.906| 1.509 |
| 17  | 436  | 4.5   | 0.65  | 1.304| 0.000| 0.0000    | 0.778| 1.676 |
| 18  | 436  | 5.0   | 0.45  | 1.359| 0.031| 0.0422    | 0.703| 1.933 |
| 19  | 436  | 5.5   | 0.50  | 1.321| 0.000| 0.0000    | 0.668| 1.977 |
| 20  | 436  | 6.0   | 0.55  | 1.300| 0.019| 0.0329    | 0.559| 2.325 |
| 21  | 448  | 4.0   | 0.65  | 1.439| 0.016| 0.0181    | 0.869| 1.655 |
| 22  | 448  | 4.5   | 0.45  | 1.355| 0.000| 0.0000    | 0.756| 1.792 |
| 23  | 448  | 5.0   | 0.50  | 1.300| 0.035| 0.0461    | 0.723| 1.798 |
| 24  | 448  | 5.5   | 0.55  | 1.361| 0.067| 0.0942    | 0.644| 2.113 |
| 25  | 448  | 6.0   | 0.60  | 1.272| 0.110| 0.1774    | 0.510| 2.459 |

5. Conclusion

(1) Taking shape coefficient, cladding layer width, height and dilution rate into consideration, the process parameters of sample 25 was finally selected. The laser power was 448W, the powder feeding speed was 9.0369g/min, and the scanning speed was 6mm/s.

(2) According to the microstructure analysis of sample 25, planar crystals, cellular crystals, columnar crystals, dendrites, coarse equiaxed crystals and fine equiaxed crystals changed gradually from the bottom of the cladding layer to the top.

(3) The transverse hardness of the sample is basically about point six symmetry. The average horizontal hardness is 663.9 HV, which is 3.04 times of the substrate hardness. The average hardness of the vertical cladding layer is 687.5 HV, which is 3.14 times of the substrate. The average hardness in the vertical direction is higher than that in the horizontal direction. The total average hardness is 672.2HV, 3.08 times of the substrate.

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References

[1] Åkerfeldt P, Antti M and Pederson R 2016 Influence of microstructure on mechanical properties of laser metal wire-deposited Ti-6Al-4V *Materials Science and Engineering: A* 674 428-37
[2] Devojno O G, Feldshtein E, Kardapolava M A and Lutsko N I 2019 On the formation features, structure, microhardness and tribological behavior of single tracks and coating layers formed by laser cladding of Al-Fe powder bronze Surface and Coatings Technology 358 195-206

[3] Lei X, Huajun C, Hailong L and Yubo Z 2017 Study on laser cladding remanufacturing process with FeCrNiCu alloy powder for thin-wall impeller blade The International Journal of Advanced Manufacturing Technology 90 1383-92

[4] Liu H, Hu Z, Qin X, Wang Y, Zhang J and Huang S 2017 Parameter optimization and experimental study of the sprocket repairing using laser cladding The International Journal of Advanced Manufacturing Technology 91 3967-75

[5] Liu Y, Liu C, Liu W, Ma Y, Tang S, Liang C, Cai Q and Zhang C 2019 Optimization of parameters in laser powder deposition AlSi10Mg alloy using Taguchi method Optics & Laser Technology 111 470-80

[6] Shihab S K, Mohamed R H and Mubarek E M 2019 Optimization of Process Parameters in Cladding of Stainless Steel over Mild Steel Materials Today: Proceedings 16 816-23

[7] Wu Y, Liu Y, Chen H, Chen Y, Li H and Yi W 2019 Microstructure evolution and crack propagation feature in thermal fatigue of laser-deposited Stellite 6 coating for brake discs Surface and Coatings Technology 358 98-107

[8] Xu J, Zhu J, Fan J, Zhou Q, Peng Y and Guo S 2019 Microstructure and mechanical properties of Ti–6Al–4V alloy fabricated using electron beam freeform fabrication VACUUM 167 364-73

[9] Yu T, Yang L, Zhao Y, Sun J and Li B 2018 Experimental research and multi-response multi-parameter optimization of laser cladding Fe313 Optics & Laser Technology 108 321-32

[10] Zhu Y, Yang Y, Mu X, Wang W, Yao Z and Yang H 2019 Study on wear and RCF performance of repaired damage railway wheels: Assessing laser cladding to repair local defects on wheels WEAR 430-431 126-36