Viser Technology Pte. Ltd.
Mechanical Engineering Science
doi: 10.33142/me.v1i2.1656

Research Article Open Access

Optimization of Process Parameters of Laser Cladding 304L Alloy Powder Based on Orthogonal Experiment

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Abstract:
In order to find the optimal combination of process parameters for laser cladding 304L alloy powder on the surface of 45 steel, a combination method of single factor test and multi-factor orthogonal experiment was used to perform the single pulse laser cladding experiment. The effects of process parameters (pulse current A, pulse width B, pulse frequency C,defocus distance D, scan velocity E) on the morphology and performance of cladding layer was studied by range analysis, and the optimal combination of cladding parameters is calculated by fuzzy comprehensive evaluation. The results show that different process parameters have different effects on the morphology of the cladding layer and scanning velocity E and defocus distance D are the most important influencing factor of cladding morphology. The effect on cladding width is D> C > A > B > E and the effect on cladding height is E > A > C > D > B. The optimal combination of cladding width is $A_4B_4C_4D_4E_2$. The optimal combination of cladding high is $A_2B_1C_1D_4E_1$. The comprehensive optimal process parameters are pulse current 210A, pulse width 3.6ms, pulse frequency 16Hz, defocus distance +10mm and scanning speed 240mm/min. The average hardness of the cladding layer, melting pool, heat-affected zone and substrate under the optimal process parameters is 406.2 $HV_{0.5}$, 470.8 $HV_{0.5}$, 230.5$HV_{0.5}$ and 202.0$HV_{0.5}$, respectively. The 304L cladding layer on 45 steel surface is stable in width, height and surface quality under comprehensive optimal parameters.

Keywords: *laser optical; the optimal process; orthogonal test; 304L alloy powder; laser cladding; fuzzy comprehensive evaluation.*

1. Introduction

Laser cladding is a coating technology that deposits multiple layers of composite material on the substrate to improve the physical properties of the work-piece such as wear resistance and corrosion resistance [1-4]. Laser cladding technology is widely used in surface enhancement and wear repair of parts[5-9]. Laser cladding technology has good adaptability and no special requirements for metal powder and substrate. It can obtain high performance alloy on cheap and low performance metal surface and can significantly improve the mechanical properties of mechanical parts[10-11].Steel 45 is a common material used in manufacturing machine parts. It has important industrial application value to prepare wear - resistant and corrosion - resistant cladding layer with high hardness on the surface of 45 steel.

At present, the research of preparing high performance alloy cladding layer on low performance metal has been published. Parekh R et al.[12]studied the optimization of cladding forming geometry and found that laser cladding process parameters had a direct impact on its geometry. Jiao X.Yet al. [13] studied the influence of scanning velocity on the microstructure of cladding layer, and found that increasing velocity would induce defects.Lei J.F et al. [14] studied the laser cladding Ni60-25% WC coating on U71Mn steel surface and obtained the optimal process parameters. ZanS.P et al. [15] studied the laser cladding technology of 316L stainless steel powder, and analyzed the effect of technological parameters on surface morphology and hardness.Xu M.S et al. [16] studied the microstructure and properties of laser cladding Ni base alloy of 45 steel. Xu Q.K et al. [17] studied the technicality of TiBCN powder CO_2 laser cladding on the surface of steel 45.Liu X.M et al. [18] studied 45 steel laser cladding Ni35B+WC alloy and found that WC content can improve the hardness and wear resistance of cladding layer. The above studies show that the process parameters are the main factors affecting the morphology, microstructure, hardness distribution and wear resistance of the coating.However, there is little literature on the cladding layer of 304L alloy on the surface of 45 steel by pulsed laser, and there is a lack of optimized process parameters. As a result, the 304L alloy powder is not widely used in remanufacturing and surface strengthening of mechanical parts.

In this paper, the process optimization of laser cladding 304L alloy powder on 45 steel surface is studied.Firstly, single-factor test and multi-factor orthogonal test are carried out to analyze the influence of each process factor on the morphology of single-pass cladding layer.Then the range analysis method is used to evaluate the significant order of the influence of each process parameter on the single-pass cladding morphology.Based on the orthogonal test results, multi-objective fuzzy comprehensive evaluation is carried out to find the comprehensive optimal combination of cladding process parameters.Finally, the stability of the synthetic optimal process is verified by the test of morphology and hardness[19-21].

2. Orthogonal Experimental Design

2.1. Experimental equipment and materials

The Nd: YAG pulse laser cladding machine with a power of 800 watts is used in the experiment.The effective range of the cladding process parameters of the equipment: pulse current is 200A~ 230A, pulse width is 3.0ms ~3.6ms, frequency is 14Hz~17Hz, defocusing amount is +8mm~+14mm, and scanning speed is 240mm/min ~330mm/min.In order to avoid mutual influence of each channel of cladding and interference of residual heat of substrate, laser beams were scanned along the same direction during the test. The spacing g between adjacent cladding strips was set to be more than 2 times of the width W of single channel of cladding, and the scanning cooling interval was set to be 10 minutes. The experimental principle was shown in Figure 1.

The particle size of 304L stainless steel alloy powder is 180-320 mesh, the loose packing density is 3.8g / cm^3, the base material is the 45 steel plate after being polished and cleaned, the length, width and height is 200mm×80mm×10mm.The mass fraction of 304L stainless steel alloy powder and 45 steel composition is shown in Table 1.

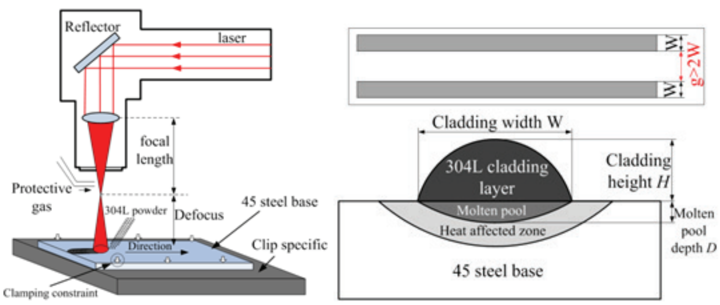


Figure 1. Schematic diagram of experimental principle of Laser cladding.

Table 1. Chemical composition of 304L stainless steel alloy powder and 45 steel substrate (wt%).

Materials	C	Si	Mn	Ni	Cr	P	S	Cu	O	Fe
304L alloy powder	≤0.03	≤1.0	≤0.2	8.0-12.0	18.0-20.0	-	-	-	≤0.15	Bal
45 steel	0.45	0.20	0.20	≤0.25	≤0.25	≤0.035	≤0.035	≤0.25	-	Bal

2.2. Design of experimental scheme

Due to the laser cladding machine used has many technological parameters and each parameter can be adjusted widely, the orthogonal experiment of multiple factors was carried out. The orthogonal experiment scheme $L_{16}(4^5)$ was designed, as shown in Table 2.

The macroscopic morphologies of 16 groups of single-pass cladding layers were obtained by orthogonal test, as shown in Figure 2. From the macroscopic morphology, the width of no. 1-2 specimen is narrow and the cladding pattern is too dense. The surface roughness of no. 3-6 specimen is relatively large, and a few powder particles are in the state of semi-melting. There is un-melted powder and uneven cladding width on the surfaces of no.9, 11, 12, 14 and 16;The surface and edge of no. 7, 8, 10 and 15 cladding layers are smooth and have good macroscopic morphology.

Table 2. Multi-factor orthogonal experimental scheme($L_{16}(4^5)$).

Number	Pulse current A	Pulse width ms	Pulse frequency Hz	Defocus distance mm	Scan velocity $mm \cdot min^{-1}$	Layer width mm	Layer height mm
1	200	3.0	14	+8	240	1.80	0.52
2	200	3.2	15	+10	270	2.12	0.38
3	200	3.4	16	+12	300	2.60	0.32

Number	Pulse current A	Pulse width ms	Pulse frequency Hz	Defocus distance mm	Scan velocity mm·min^{-1}	Layer width mm	Layer height mm
4	200	3.6	17	+14	330	3.06	0.30
5	210	3.2	14	+14	300	2.32	0.58
6	210	3.0	15	+12	330	2.48	0.38
7	210	3.6	16	+10	240	2.66	0.54
8	210	3.4	17	+8	270	2.54	0.40
9	220	3.4	14	+10	330	2.36	0.32
10	220	3.6	15	+8	300	2.58	0.30
11	220	3.0	16	+14	270	2.92	0.56
12	220	3.2	17	+12	240	2.80	0.42
13	230	3.6	14	+12	270	2.86	0.38
14	230	3.4	15	+14	240	2.98	0.44
15	230	3.2	16	+8	330	2.54	0.30
16	230	3.0	17	+10	300	2.72	0.30

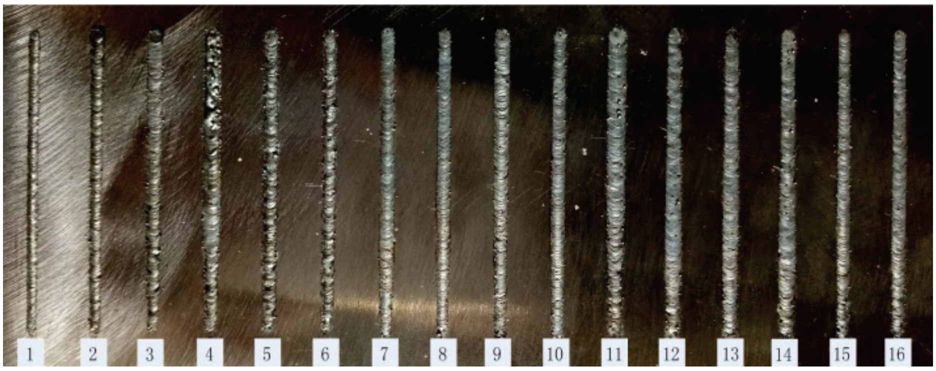


Figure 2. Multi-factor orthogonal experimental results.

3. Results and Discussion

3.1. Section morphology analysis

The cladding layer was cut along the direction perpendicular to the cladding, the cross section of cladding layer was observed by optical microscope, and the cross-section morphologies of 16 groups of samples were obtained, as shown in Figure 3. As it can be seen from the figure, No. 1 cladding layer is height and narrow; No. 4, 9, 15 and 16 cladding layers are relatively flat, and the height and width do not meet the cladding requirements;No. 2, 6, 10 and 14 cladding layers are unevenly distributed and convex, and the cladding layer is not well fused;The surface of No. 3, 5, 7, 8, 11, 12 and 13 cladding layers is flat and has better height and width.

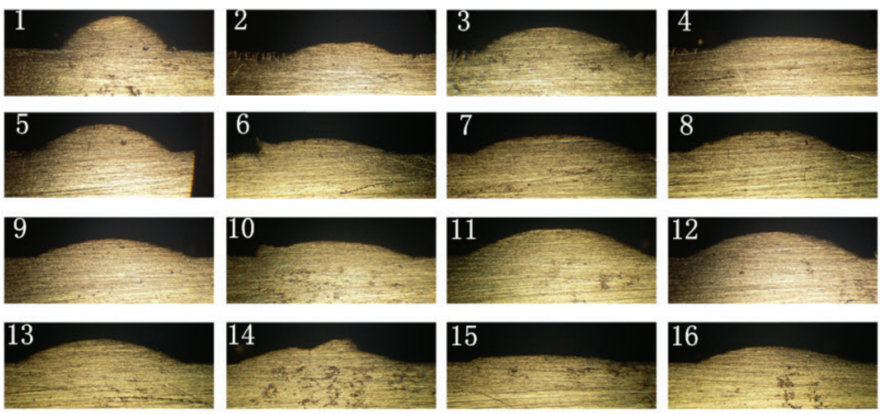


Figure 3. Cross-section microscopic image of a single laser cladding layer in orthogonal test.

3.2. Range analysis

Set T_{ij} be the sum of experimental results y_m (y_1 and y_2 are the width and height of cladding layer, respectively) at the level j in column i. K_{ij} is the experimental mean value at the j-th level of column i. R is the range value of column i, indicating the range of variation of the test index within the value range of this factor. Max (K) and min(K) are the maximum and minimum K values in column i respectively. In formula (1), j is the number of levels, i is the number of columns, namely the number of factors (A, B, C, D, E), and r is the number of repeated tests at the same level in a certain factor.

$$\begin{cases} T_{ij} = \sum_{j=1}^{4} y_m \\ K_j = \frac{T_j}{r} \\ R = \max(K) - \min(K) \end{cases} \quad (1)$$

The range analysis can determine the primary and secondary factors that affect the experimental results. The large range indicates that the factor has a great influence on the experimental results, and it is the main factor.The small range indicates that this factor has a great influence on the experimental results, and it is a secondary factor.

The width and height of the cladding layer are measured by the microhardness tester, and the range analysis results of laser cladding test results are calculated by using formula (1), as shown in Table 3. It can be seen from the Table 4 that the main factor affecting the cladding layer width is scanning speed E, and the corresponding optimal combination is $A_4B_4C_4D_4E_2$.The main factor affecting the cladding layer height is also the scanning speed E, whose optimal combination is $A_2B_1C_1D_4E_1$.The effect of scanning speed on height and width of the cladding layer is the main factor, the focal length has a greater effect on the width of the cladding layer and the least effect on the height, and the effect of pulse width and frequency on the height and aspect ratio of the cladding layer is in the middle level.

Table 3. Range analysis.

Items		Pulse current Factor A	Pulse width Factor B	Pulse frequency Factor C	Defocus distance Factor D	Scan velocity Factor E
The width of the cladding layer mm	T_{i1}	9.58	9.92	9.34	9.46	10.24
	T_{i2}	10.00	9.78	10.16	9.86	10.44
	T_{i3}	10.66	10.48	10.72	10.74	10.22
	T_{i4}	11.10	11.16	11.12	11.28	10.44
	K_{i1}	2.40	2.48	2.34	2.36	2.56
	K_{i2}	2.50	2.45	2.54	2.47	2.61
	K_{i3}	2.67	2.62	2.68	2.69	2.55
	K_{i4}	2.78	2.79	2.78	2.82	2.61
	R	0.38	0.35	0.45	0.46	0.06
		The precedence order of the factors: D> C >A> B>E				
	Optimization levels	A_4	B_4	C_4	D_4	E_2
	Optimal combination	$A_4B_4C_4D_4E_2$				
The high of the cladding layer mm	T_{i1}	1.52	1.76	1.80	1.52	1.92
	T_{i2}	1.90	1.68	1.50	1.54	1.72
	T_{i3}	1.60	1.48	1.72	1.50	1.50
	T_{i4}	1.42	1.52	1.42	1.88	1.30
	K_{i1}	0.38	0.44	0.45	0.38	0.48
	K_{i2}	0.48	0.42	0.37	0.39	0.43
	K_{i3}	0.40	0.37	0.43	0.38	0.38
	K_{i4}	0.36	0.38	0.35	0.47	0.32
	R	0.12	0.07	0.10	0.09	0.16
		The precedence order of the factors: E>A>C>D>B				
	Optimization levels	A_2	B_1	C_1	D_4	E_1
	Optimal combination	$A_2B_1C_1D_4E_1$				

Range analysis cannot directly reflect the optimal results under the control of multiple indexes, and comprehensive evaluation is needed to determine the comprehensive optimal process parameter combination. Therefore, the surface height and width indexes of 304L laser cladding layer are comprehensively analyzed by fuzzy comprehensive evaluation method.

The specific methods of comprehensive analysis are:

Firstly, the fuzzy judgment matrix is obtained through the comment set of each sample factor set, and the weight judgment matrix of each evaluation index is obtained through expert knowledge and experience.

Then, the analytic hierarchy process (AHP) is used to analyze the weight consistency index and find the objective weight coefficient of each evaluation index.

Finally, fuzzy operator is used for fuzzy comprehensive evaluation.

The fuzzy comprehensive evaluation factor set: {cladding height, cladding width}, comment set: {good, relatively good, general, bad, poor}.The evaluation of cladding height $\widetilde{H}_i$ and cladding width $\widetilde{W}_i$obtained the fuzzy matrix $\widetilde{F}_i$ (i= 1,2,3…16,Where i is the serial number of cladding strip), the first row of the matrix $\widetilde{F}_i$ values from $\widetilde{H}_i$, and the second row values from$\widetilde{W}_i$.

The *zadeh* operator is used to conduct compound operation on the fuzzy matrix to get the evaluation result $\widetilde{Z}_i$, and the normalized processing is done $\widetilde{Z}^*_i$ (i= 1,2,3...16), as shown in Table 4. As can be seen from Table 4, $\widetilde{Z}^*_7$ and $\widetilde{Z}^*_8$ should be the highest level, from the level of "good" quality, the comprehensive optimal result is $\widetilde{Z}^*_7$. In other words, the comprehensive optimal process parameters are current 210A, pulse width 3.6ms, frequency 16Hz, defocusing amount +10mm, and scanning speed 240mm/min.

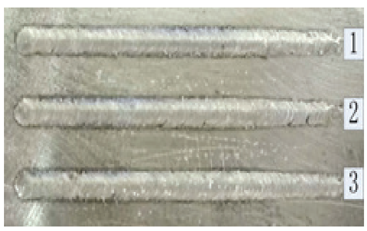
Table 4. Evaluation results of fuzzy matrix.

$\widetilde{Z}^*_1$=（0.14，0.43，0.29，0.14，0.00）	$\widetilde{Z}^*_2$=（0.10，0.50，0.40，0.00，0.00）
$\widetilde{Z}^*_3$=（0.00，0.20，0.40，0.40，0.00）	$\widetilde{Z}^*_4$=（0.00，0.11，0.22，0.44，0.22）
$\widetilde{Z}^*_5$=（0.00，0.23，0.31，0.31，0.15）	$\widetilde{Z}^*_6$=（0.00，0.08，0.46，0.31，0.15）
$\widetilde{Z}^*_7$=（0.42，0.42，0.17，0.00，0.00）	$\widetilde{Z}^*_8$=（0.36，0.55，0.09，0.00，0.00）
$\widetilde{Z}^*_9$=（0.30，0.30，0.40，0.00，0.00）	$\widetilde{Z}^*_{10}$=（0.08，0.25，0.50，0.17，0.00）
$\widetilde{Z}^*_{11}$=（0.09，0.18，0.55，0.18，0.00）	$\widetilde{Z}^*_{12}$=（0.09，0.18，0.55，0.18，0.00）
$\widetilde{Z}^*_{13}$=（0.00，0.30，0.60，0.10，0.00）	$\widetilde{Z}^*_{14}$=（0.00，0.10，0.50，0.40，0.00）
$\widetilde{Z}^*_{15}$=（0.00，0.17，0.42，0.42，0.00）	$\widetilde{Z}^*_{16}$=（0.08，0.23，0.46，0.31，0.00）

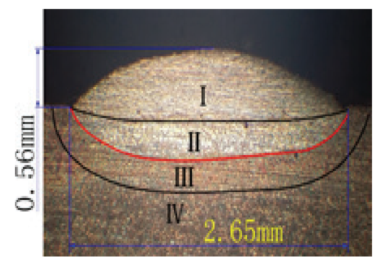
3.3. Hardness testing

Through the results of fuzzy comprehensive evaluation, it can be found that when the scanning speed and defocus are controlled in the range of 240 ~ 270 mm/min and + 8 ~ 10 mm respectively, the cladding layer with better surface shape and no crack defects can be formed. Figure 4 (a) shows the three single-pass cladding morphologies under the optimal process parameters.It can be seen from the Figure 4 (a) that the surface of the cladding layer (No. 1, No. 2 and No. 3) is smooth and continuous, with uniform height and width, and good formation. The cladding width is 2.54mm, 2.56mm and 2.54mm, and the height is 0.56mm, 0.54mm and 0.54mm, respectively. Figure 4 (b) shows the cross section morphology of the cladding layer corroded by 4% nitric acid alcohol in No. 1. It can be seen that the cladding layer has a good bond with the substrate, and no cracks, pores and other defects are found.

The micro-hardness of the No. 1 cladding sample in Fig. 4b was observed, and 11 measuring points were set along the vertical direction on the section. The measuring point distribution in the cladding layer Ⅰ molten pool Ⅱ, Ⅳ,III heat-affected zone and the 45steel base Ⅳ, respectively(as shown in Figure 5 (a). HV-1000 micro-hardness tester was used to measure the hardness of cladding samples (KGF =0.5), and the test results were shown in Figure 5 (b). By the figure shows, molten pool Ⅱ has the highest hardness and as depth increases, the hardness of cladding layer Ⅰ value is higher, but lower than the molten pool Ⅱ matrix Ⅳ minimum hardness, the hardness of heat affected zone Ⅲ hardness value rapid transition from high to low hardness value, the final hardness is only slightly higher than the base material.Cladding layer Ⅰ, molten pool Ⅱ, heat affected zone Ⅲ and Ⅳ average hardness are 406.2 $HV_{0.5}$、470.8$HV_{0.5}$、230.5$HV_{0.5}$、202.0$HV_{0.5}$, respectively. The average hardness of the cladding layer Ⅰ is 2.33 times of the 45 steel substrate Ⅳ.



(a)morphology



(b)the cross section shape.

Figure 4: Three single-pass cladding morphologies under the optimal process parameters

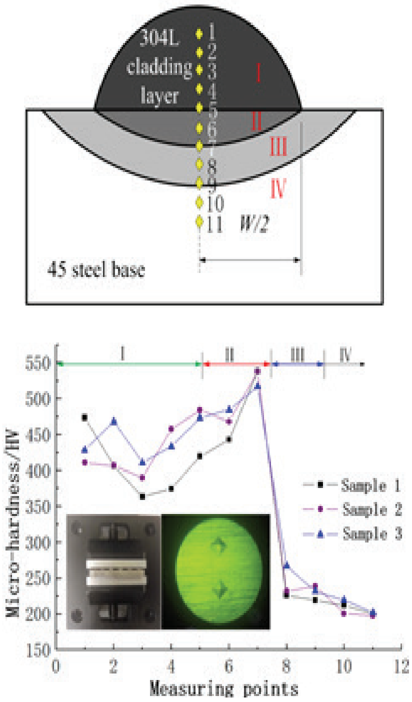


Figure 5. The micro-hardness of the cladding sample (a) position of measuring points;(b)hardness distribution curves.

Conclusions

The influence degree of different process parameters on the cladding layer morphology is found by range analysis of orthogonal test results. From the effect on cladding width, defocus distance D> frequency C > current A > pulse width B> scanning speed E. From the effect on cladding height, scanning speed E > current A > frequency C >defocus distance D > pulse width B. The scanning velocity E and defocus distance Dare the most important factor affecting the cladding layer morphology.

The comprehensive optimal combination of cladding process parameters is current 210A, pulse width 3.6ms, frequency 16Hz, defocusing amount +10mm, scanning speed 240mm/min.The single pass cladding layer has good surface finish, stable width and height, good bonding between the cladding layer and the substrate, and no cracks, pores and other defects.

Under the comprehensive optimal process parameters, the average hardness of cladding layer, molten pool, heat affected zone and substrate is 406.2$HV_{0.5}$, 470.8$HV_{0.5}$, 230.5$HV_{0.5}$ and 202.0$HV_{0.5}$, respectively. The average micro-hardness of cladding layer is 2.33 times that of 45 steel substrate, and the surface hardness of the substrate after cladding is significantly improved.

Acknowledgements: This work was supported by the National Natural Science Foundation of China (No.51505268),Key project of shaanxi provincial science and technology department (2017ZDXM-GY-138) and Shaanxi provincial education department special research program (16JK1139).

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