The Study of Laser Milling on Curved Surface Cladding Parts Based on the Orthogonal Experiment

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Abstract-When thin-walled parts are forming by laser cladding method, arc and uneven surfaces will be caused. This kind of phenomenon will become more serious with the increasing layers, and impact a lot on the quality. In order to improve the forming quality, laser milling is used to machine the curved surface of cladding parts. Through the orthogonal experiment on single channel laser cladding parts, factors like point space, average power, pulse width and focal distances which impact the milling depth of curved surface are studied, and their influence weight and rule are also obtained, and milling quality of surface is optimized at the same time. According to the test result, stability of multilayer milling is verified by taking multilayer milling on thin- walled metal parts. That the total milling depth is 0.479mm and the surface roughness of cladding parts is 4.517um after milling. Effective and accurate milling is realized while form quality is also improved.

Index Terms—Surface machining, laser milling, design optimization, orthogonal design, rough surface.

I. INTRODUCTION

Direct deposition of metallic parts has held the researchers' wide interests both at home and abroad. And it is applied to some fields successfully, but in the process of laser direct metal forming, the process parameter is more. And any uncertain parameters will make forming surface become uneven [1], [2]. In particular, it will make the cladding parts surface curved and seriously affect the forming quality, even lead that subsequent forming cannot be proceed. In order to guarantee the forming quality, the curved surface is need to be milled in cladding forming process. So the surface of the cladding parts will be fat, thus ensure the quality of the final forming of the cladding parts. Therefore, many scholars put forward a complex technique that the combination of direct rapid manufacturing and mechanical milling or laser milling. In the process of forming aided mechanical milling or laser milling, this way improves the quality and precision of the side surface of the forming parts to a certain extent [3]-[6]. But the method of mechanical milling has disadvantages. For example, the forming parts' surface hardness is high because of rapid condensation, so it is great difficulties to process the forming parts by mechanical milling. And machine finishing need to sectional fixture, what is worse, machining complex shape parts need to sectional fixture more times, it will result in process increasing and efficiency decreasing [7]-[9].

Comparing with mechanical milling, the laser milling has a lot of advantages. For example, in principle, it can mill any solid material by laser ablation of high peak power. Because the laser ablation is instantaneous thermal evaporation process of minimal heat affected zone and the milling process is independent of the hardness of the work material [10]. What's more, the laser milling is without tool wear and it can complete precision machining of all geometrical shape [10]. So far, the current researches about laser milling cladding parts only confined to influences of different milling process parameters on the surface roughness of cladding parts [11]. Due to the processing quality of curved surface is also determined by other factors, and in these factors, the milling depth of cladding parts curved surface has a great influence on the processing quality. So this paper mostly focused on the study of processing cladding parts surface by laser milling from these two aspects. Through the orthogonal experiment on single channel laser cladding parts, the weight and influence law that the point spacing, average power, pulse width, focal distances of the four factors on milling depth of the cladding parts curved surface has been obtained. According to these results of the study, the possibility about finishing the cured surface of the laser cladding by laser milling explored to improve the forming quality and precision of the cladding parts.

II. THE PRINCIPLE OF MILLING CLADDING PARTS BY LASER

Submit your manuscript electronically for review. Laser milling use high energy laser beam to the surface of the cladding. So the temperature of the cladding parts which are irradiated on by laser rises in a very short time. These parts are melting rapidly and the molten metal will be ejected rely on the strong pressure of assistant gas. Thus, the quality transport process is completed. The key factors of influencing the material melting or gasification are the laser power density which effect on the surface and the laser absorption of materials. The laser used in this article is Nd: YAG laser, the calculation formula of instantaneous power density at the waist place of laser beam as shown in formula 1.

$$P_0 = \frac{4P_a}{\pi t f D^2} \tag{1}$$

In the formula, the P_0 is instantaneous power density at the waist place of laser beam, the P_a is output power, the *t* is pulse width, the *f* is repetition frequency, the *D* is spot diameter.

The laser energy density is the highest near the beam waist. However, in order to meet the need of processing technology, different focal distances will be chosen in the experiment. So

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it is need to calculate the energy density in the case of different focal distances, the calculation formula is shown in formula 2.

$$P(r) = P_0 \times \exp(-2 \times \frac{r^2}{w_0})$$
(2)

In the formula, the P_r is energy density, the *r* is Gaussian beam radius of any place, the w_0 is Gaussian beam radius of waist place.

From the above formula we can see that increasing the output power or reducing the spot diameter and pulse width can improve the laser energy density. And regulation the defocusing amount also can change the laser energy density. So these factors should be studied in the following experiment.

What's more, when thin-walled parts are forming by laser cladding method, arc and uneven surfaces will be caused. This kind of phenomenon will become more serious with the increasing layers, and impact a lot on the quality. The milling and chip-removal model is shown in Fig.1, that laser milling the curved surface of laser cladding parts under pulsed laser which is in a certain overlap-rate. The surface of cladding parts become melt and partial vaporization after laser irradiation. Under the effect of vector resultant force which contains assist gas pressure, gravity and steam inflationary pressure, the molten metal liquid flowing from a pit to another pit which is formed in the former pulse time. This will make the metal liquid which is in the raised sections of the curved surface flow to the low sections. So the entire curved surface become more flat. And it could be fount out that the slop of curved surface is reduced as shown in the model (Fig. 1).



Fig. 1. The chip-removal model of laser milling curved surface.

III. EXPERIMENTAL RESEARCH

A. Experimental Material

The 304 stainless steel as matrix material was used in the test, and the size of matrix is 150mm long, 60mm wide and 10mm high. The laser cladding parts were formed by YLS-2000 fiber laser based on hollow-laser beam inside F313 alloying powder feeding technology [12]. Five single pass cladding parts with three layers were formed on the matrix as shown in Fig. 2. The process parameters of laser cladding are 800W average power, 7mm/s speed, -4mm focal distances and 2r/min feeding speed. The shielding gas is nitrogen.



Fig. 2. Single pass cladding parts with three layers.

B. Experimental Setup

The laser milling equipment is Nd:YAG pulse solid laser. it's maximum power is 300W, the wavelength is 1064nm, and the focal length is 110nm. Refer to Fig.3. In the test, the frequency is fixed at 30Hz, the auxiliary gas is argon gas, and the gas flowing speed is 8L/min. So milling the cladding parts under the auxiliary gas can ensure that there no surface oxidation. Then using a resolution of 0.001 micro micrometer to measure the depth of the cladding parts surface after laser milling. And using ADE MocroXAM 3D profilometer to measure roughness of the surface.



Fig. 3. Nd:YAG pulse solid laser.

C. Orthogonal Experiment

There four milling process parameters are determined to be researched in the test, these parameters are point spacing (A), average power (B), pulse width (C) and focal distances (D). All factors are set three levels. These selected factors and levels are based on (my)earlier studies (that myself have researched as) that myself have researched as shown in Table I.

TABLE I: FACTOR AND LEVELS OF ORTHOGONAL TEST									
Level of factor	Point spacing A(mm)	Average power B(W)	Pulse width C(ms)	Focal distances D(mm)					
1	0.08	90	2	-1					
2	0.1	100	3	-0.5					
3	0.12	110	4	0					

The results of orthogonal experiment according to the laser process parameters in Table I are shown in Table II. And the physical picture of the cladding parts after laser milling as shown in Fig. 4.

We can see from Table II, the influence sequence can be concluded that the sequence were A>C>B>D by comparing the milling depth under the range (R) of the index factors. In particular, the effect of point spacing is the biggest and the effect of focal distances is the smallest. What's more, the optimum parameters of the milling depth by laser milling through analyzing range. When the point spacing is 0.07mm, the milling depth is maximum through comparing the values $(k_1, k_2 \text{ and } k_3)$ under the factor of point spacing (A) as shown in Table II. Similarly, the values of average power (B), pulse width (C) and focal distances (D) also can be get what can make the milling depth maximum. So the optimal solution is $A_1B_3C_3D_3$, that the values are 0.07mm of point spacing, 110W of average power, 4ms of pulse width and -0.5mm of focal distances.

TABLE II: EXPERIMENTAL SCHEME AND RESULT OF ORTHOGONAL TEST

No.	I	Points bacing	Average power	Pulse width	Focal distance	s depth	
		/mm	/W	/ms	/mm	/mm	
1		0.07	90	2	-1.5	0.141	
2		0.07	100	3	-1	0.520	
3		0.07	110	4	-0.5	1.33	
4		0.1	90	3	-0.5	0.072	
5		0.1	100	4	-1.5	0.12	
6		0.1	110	2	-1	0.088	
7		0.13	90	4	-1	0.071	
8		0.13	100	2	-0.5	0.043	
9		0.13	110	3	-1.5	0.066	
	K_1	1.991	0.2	284	0.272 ().327	
	K_2	0.28	0.6	583	0.658 ().679	
	K_3	0.18	1.4	184	1.521 1	.445	
	k_1	0.664	0.0)95	0.091 ().109	
	k_2	0.093	0.2	228	0.219 ().226	
	k_3	0.06	0.4	495	0.507 ().482	
	R	0.604	0	.4	0.416 ().373	
(Optimal solution	A_{l}	Η	B ₃	<i>C</i> ₃	<i>D</i> ₃	
l	Influence	A > C > B > D					



Fig. 4. The physical picture of the single-channel cladding part after laser.



Fig. 5. The low power and high power micro-graph after laser milling by optimal solution $A_1B_3C_3D_3$ (a) low power micro-graph; (b) high power micro-graph.

Fig. 5 is the low power and high power micro-graph of the cladding parts after laser milling by the optimum parameters noted above. It is apparent that there are more black slag in the middle section and edges collapse seriously as shown in the figure. What is worse, there are large slag accumulation area can be seen in the high power micro-graph. So we can't keep the optimal value of the milling depth as the optimal parameters of laser milling.

According the single factor experiment of processing cladding parts through laser milling studied by Hang Xiaolin

[11]. We can know that, the surface roughness of cladding parts after laser milling is better under low laser power. But analyzing the milling depth, the average power has a greater influence on it. As the laser power is low, the milling depth reduce rapidly. So, the milling depth and surface roughness need to be considered together. The average power is set at 100W, and selecting three samples (No.2, No.5 and No.8) from the orthogonal test as shown in Table II. Then measuring the average surface roughness through three areas of every sample, the values of surface roughness were 5.684 um, 6.293 um, 6.961um, the gap between them is small. Considering the cladding parts laser milling is micro plastic (the milling depth is less than 0.5 mm), the milling depth of sample 2 is too big and the milling depth of sample 8 is too small to affect the milling efficiency. So selecting the parameters of sample 5 as the optimal parameters of milling the cladding parts surface, that the values are 0.1mm of point spacing, 100W of average power, 4ms of pulse width and -1.5mm of focal distances.



Fig. 6. The comparison chart of cladding surface between before milling and after milling.(a) low power micro-graph; (b) high power micro-graph before milling; (c) high power micro-graph after milling; (d) surface roughness before milling; (e)surface roughness before milling.

Fig. 6 is the comparison chart of cladding surface between before milling and after milling. It is observed that the surface is more brightness after milling from low power micro-graph. And the convex slope is slow can be seen in the high power micro-graph. What's more, we can see that the surface quality is improved obviously compared with the original cladding parts from Fig. 6(d) and Fig. 6(e). Specifically, the height difference of the highest point and the lowest point decreased form 40 um to 30 um after milling. And the surface roughness decreased form 8.623um to 4.529um.

D. Verification Test of Multilayer Milling

The stability of laser milling that the changes of milling depth of surface, milling width of side and surface roughness should be considered when milling the cladding parts by layers. While milling the layers of surface, if keeping the focus position still, the spot diameter gets bigger with the increase of milling depth, and the laser energy density is also decreased, causing the milling depth is smaller. Same would happen while milling the layers of side with the center of light spot walking along the edge of cladding parts, the laser energy density would also be decreased, causing the milling width is decreased. So, it is would be necessary to drop a single milling depth after milling each layer to make the focus position stays still. Then milling the layers of cladding parts with process parameters as shown in Fig. 7. The milling depth is 0.358mm and the surface roughness is 6.182um. In general, the change of milling depth, milling width and surface roughness is very small, so the effect of multilayer milling is stable.



Fig. 7. The macro profile of cladding parts surface after multilayer milling.

IV. CONCLUSION

In this case, through the test of milling the curved surface of cladding parts by laser on single channel cladding based the orthogonal experiment, the factors affecting the weight and influence law on milling depth of the curved surface were obtained, which are the point spacing, average power, pulse width, focal distances. Among of them, point spacing is the most significant factor. The optimized parameters of single layer milling by laser were got, considering these factors affecting the surface roughness of cladding parts, they are 0.1mm of point spacing, 100W of average power, 4ms of pulse width and -1.5mm of focal distances.

According to the test result, stability of multilayer milling is verified by taking multilayer milling on thin- walled metal parts. That the total milling depth is 0.479mm and the surface roughness of cladding parts is 4.517um after milling. The high precision milling on curved surface of cladding parts is realized while form quality is also improved. It was verified that laser milling could improve the forming quality of cladding parts.

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