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Optimization for Morphology of Grinding Layer on Textured Laser Cladding Grinding Tool

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Abstract

In order to improving the grinding performance of laser cladding textured grinding tool (LCTGT) under high speed grinding process, the topography shape (height, width and height/width ratio) of laser cladding grinding layers on LCTGT were designed with RSM (response surface method) through optimizing laser cladding processing parameters and laser cladding layers structure parameters that based on Archimedes helix coefficients. The LCTGTs were produced with optimized laser cladding parameters and structural parameters for laser cladding grinding layers. The results showed that laser cladding parameters of 397W of laser power, 3.56 mm/s of the laser scanning speed and 0.91 r/min of powder feeding rate and structure parameters of laser cladding layers of 6-10-10 can meet requirement.

Keywords RSM, ANOVA, textured grinding tool, grinding, laser cladding, parameters optimization

1 Introduction

Grinding tools play great roles for the quality of workpieces during grinding process. Various materials with different machining environment need to be ground by different types and specifications grinding tools [1]. For example, electroplated grinding tools have long service life [2,3] under high speed and super high speed grinding process. Brazing grinding tools possess strong chemical bonding

between abrasive and alloy matrix with high protrusion of abrasive [4]. Resin grinding tools have properties of self-sharpness, elasticity and shock resistance [5]. Ceramic grinding tools are widely used with low thermal expansion coefficient, high strength and heat resistance [6,7]. Textured grinding tools are engineered topography of these grinding wheels mentioned above to improve grinding quality [8]. Textured grinding tools possess merits of low grinding temperature, transport channel for liquid coolant that can improve the lubricating and cooling during grinding, and also reducing grinding forces [9-13] .

There are many ways to producing textured grinding tools, for example, Xiaohong Zhang et al. were inspired by nets structure from leaf vein of green plants, bronze diamond grinding tools with leaf vein structure are designed and produced by pulse laser sintering. Based on comparing grinding data from textured grinding wheels and conventional grinding wheels, the normal grinding forces and tangential forces of textured grinding wheels decreased by 12.7% to 55.8% and 8.1% to 40.3% respectively. The finish of workpieces zirconia is smoother ground by textured grinding wheels than that of conventional grinding wheels [14]. In order to improving machining stability, reducing heat loss, achieving good workpiece quality and ensuring high material removal rate, the distribution of abrasive particle on the surface of electroplating grinding wheel was designed by J. C. Aurich et al.. The parameters to be considered include the distance between the abrasive lines, the arrangement of the abrasive grains, the included angle of the abrasive lines on the circumferences of the grinding tool, the axial distance between the two abrasive lines and the corresponding abrasive grits, the geometry of the single abrasive grits, and the distribution of the size of the abrasive grits [15]. Eraldo Jannone da Silva et al. proposed that the friction lubrication effect of the cavity on the workpiece surface can be similar to the friction lubrication effect of the small bearing on the workpiece. So it is necessary to find a low cost, short production cycle machining method of the workpiece surface cavity. In this case, the surface

of traditional ceramic bond grinding wheel is deeply dressed by using diamond pen, which makes the engineered surface form and puts forward a grinding strategy to get structured workpiece. Through controlling the grinding strategy with the grits wheel, the forming of concave surface of workpiece can be controlled [16]. As the cooling fluid cannot directly reach the grinding zone due to the effect of air barrier during grinding process, Jarosław Sieniawski et al. proposed that a coolant filling method by adding cooling fluid directly to the grinding wheel hub. The coolant can be ejected from surface of excircle of grinding wheel with centrifugal force. In this case, the amount of coolant used is reduced by 10 times, and the quality of workpiece surface is improved compared with that of traditional grinding wheel grinding GrV12 steel under the same processing parameters [17]. C. Walter et al. pointed out that using ultra-short pulse picosecond laser to dress and produce structured grinding wheel can overcome the size and kinematic constraints that occurs from dressing tools. The flexibly structured surface of grinding wheel can be sintered by ultra-short picosecond laser beam with microns high geometric accuracy. Comparing with the traditional SiC grinding wheel, the grinding force of SiC grinding wheel with structured surface sintered by ultra-short pulse picosecond laser is reduced by 54%, and the surface finish of the workpiece is greatly improved [18]. The mixed diamond and metal powders (Cu-Sn-Ti) in a certain proportion (5.4%, 13.5%, 7.5% and 25%) were fused to a medium carbon steel substrate by continuous lasers and pulse lasers to produce grinding tools, which proposed by Iravani et al.. The effects of scanning speed and laser power on cladding layer, porosity, micro crack, graphitization of diamond, chemical composition of powder and diamond powder and distribution of diamond particles are discussed. The reaction layer between powder and diamond is detected and analyzed. By comparing continuous laser processing with pulse laser processing, pulse laser has lower carbonization layer and finer TiC layer at the same laser power and scanning speed. It provides a

technical basis for the fabrication of laser cladding structural grinding wheel [19]. In order to solve the problem that traditional machining methods and micro-machining tools are difficult to obtain enough precision micro-grooves of injection molds, a rotating EDM corrosion machining method was proposed for micro-grinding tools, and a high-precision matrix micro-CBN grinding tool was obtained to process multi-matrix micro-grooves of NAK80 steel discussed by Shun-Tong Chen et al.. In this way, cost is saved and ideal precision surface topography of NAK80 steel with multi-matrix microgrooves are obtained [20]. Designed pores size and shape uniformly distributed on AISI10Mg metal bond diamond grinding wheel was fabricated by Tian with using laser selective sintering technology. The purpose of making this kind of structured grinding wheel is to overcome the disadvantages of traditional metal bond grinding wheel, such as poor chip tolerance, poor self-sharpening, poor dressing ability, and easy to burn for workpieces when grinding [21].

However, designing and optimizing for the topography of textured grinding layers which in favor of high speed grinding on LCTGT has not been reported yet. In this case, in order to getting LCTGT for high speed grinding process with high precision of ground workpieces, the laser cladding parameters were optimized by RSM and multi-objective optimization method to modify cross-section of morphology of laser cladding grinding layers on LCTGT. And also, the parameters for macro structure of laser cladding grinding layers with Archimedes helix shape were selected through analyzing abrasive trajectories on grinding layers and air flow and pressure field on non-grinding zone. Then, with the optimized laser cladding parameters and structural parameters of laser cladding grinding layers, LCTGTs were fabricated.

2 Grinding angle analyzing for LCTGT

Laser cladding processing parameters have great influence on mechanical properties and

physiochemical properties of laser cladding layer. Meanwhile, the geometric shapes of laser cladding layers are determined by laser cladding process parameters. And chip space for chip flow and heat dissipation capability during grinding process are affected by geometric shapes of laser cladding grinding layers on LCTGTs[22]. The qualities of geometric shape of laser cladding grinding layer refer to width, height, height-width ratio, dilution between laser cladding layer and substrate, bonding capability between laser cladding layer and grit, cutting edges integrity of CBN grits, which the surface qualities of machined workpiece are impacted. The cross section of geometric shape for laser cladding layer is shown in Fig. 1.

Figure 2 shows schematics of cross section of various morphology of LCTGTs during grinding. From Fig. 2(a), it can be seen that the processing can be compared to milling process because of the high cutting depth, when the height is high while, the width is short and laser cladding layer edge angle θ is close to 90° . However, layers cracking phenomenon is taken place as the height of laser cladding layer is high and width of laser cladding layer is short, which lead to high stress between substrate and layer during high depth grinding process, shown in Fig. 3.

On the other side, there will be no layer fracture when laser cladding grinding layer has a large height and width under heavy load grinding process of LCTGT. And also, the grinding performance of LCTGTs can be maintained with grinding time increasing whether in the surface grinding or free surface grinding process. But, when laser cladding grinding layer is short enough for LCTGT, shown in Fig. 2 (b), (d), collision between substrate and workpiece cannot be avoided, and process safety factors cannot be guaranteed. The worst type of laser cladding layer is shown in Fig. 2 (d), the height and width are both short, in this case, the grinding quality, grinding life span and safety factors all cannot be guaranteed. In this case, the ideal condition of geometric morphology for laser cladding grinding layer

is shown in Fig. 2 (C).

Fig. 1 Cross section of laser cladding grinding layer

Fig. 2 Types for laser cladding grinding layers

Fig. 3 Layers fracture

3 Laser cladding process parameters optimizing by response surface method (RSM)

3.1 Response surface method theory

In 1951, Box and Wilson proposed response surface method (RSM) which has been widely used

in various fields[23]. Response surface method theory has been commonly recognized as an important method in experimental design method. The theory can be shown:

An exception of a function $\eta = E(y)$ is related to experimental variables $x_1, x_2, \dots, x_k$, η can be expressed by function (1):

$$\eta = f(\theta_1, \theta_2, \dots, \theta_p; x_1, x_2, \dots, x_k) + \epsilon \quad (1)$$

In function (1), $\theta_1, \theta_2, \dots, \theta_p$ are system parameters, ϵ is error and k is number of variables.

Response value η of response surface function (1) can be replaced by a step function $g(\beta_n, x_m)$, which the step function $g(\beta_n, x_m)$ is an approximate function for function (1). The first-order polynomials of function g :

$$g = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k + \epsilon \quad (2)$$

And the second-order polynomials of function g :

$$\eta = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_k x_k + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \dots + \beta_{k-1,k} x_{k-1} x_k + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \dots + \beta_{kk} x_k^2 + \epsilon \quad (3)$$

In functions (2) and (3), $\beta_0, \beta_1, \beta_2, \dots$ are approximate fitting parameters based on experimental results.

3.2 Experimental results analyzing

The purposes of optimizing B₄C/CBN/CuSnTi laser cladding process parameters (including laser power, laser scanning speed, and powder feeding rate) are to get propitiate grinding layer morphology (including height, width and height-width ratio) for LCTGTs, enhance grinding capability and efficiency of LCTGTs during grinding. Two steps are contained in the experiments, first is to find fitting relationship between heights, widths and height-width ratio of laser cladding grinding layer and laser cladding process parameters, and then, find a group of optimized laser cladding process parameters for LCTGTs

producing.

Laser cladding process parameters experiments are designed by response surface method with central composite design (CCD) algorithm. The modern experimental designing software, Design-expert 8, as supplementary for experimental data designing and analyzing. In order to fitting accurate functions related between laser cladding layer morphology and laser cladding parameters based on experimental results, two-order fitting function is adopted, shown in function (3).

Three factors, laser cladding power (P), laser scanning speed (V), and powder feeding rate (F), as experiments optimized aiming parameters, and 5 levels of each factors are selected. These 5 levels are high level (+1), low level (-1), middle point (0) and value α (± 1.68). The laser cladding experiment with 20 trials in order are conducted. The height, width and height-width ratio of cross section of laser cladding layer are measured. Experiments parameters are shown in Table 1.

The tracks of laser beam scanning are 20 single lines with 6mm long and 5mm pitches away from each other in this experiment. The laser cladding process orders is in accordance with table 2 and laser cladding process is carried out in turn. After laser cladding, each single track was cut in to 3 equal parts along the direction of cross section of laser cladding layers. Each cross section was ground by SiC abrasive papers and diamond polishing agent to reach mirror-like finish. After mirror-like finish processing, each cross section of laser cladding layers was measured by LSCM to require the dimension data. Table 2 shows average results of each dimension parameters including height, width and height-width ratio average measurement results.

Table 1 laser cladding parameters with three factors and three levels for RSM

Experiment level	-1.68	-1	0	1	1.68
Experiment factor					
Laser power P(W)	304.6	325	355	385	405.4

Laser scanning speed V(mm/s)	1.82	2.5	3.5	4.5	5.18
Powder feeding rate F(g/s)	4.64	6	8	10	11.36

Table 2 CCD experimental order and results

Order	Laser power P(W)	Scanning speed V(mm/s)	Feeding rate F(g/s)	Height H(mm)	Width W(mm)	Height-width ratio H/W
1	-1	-1	1	0.42	0.72	0.58
2	0	0	0	0.59	0.72	0.82
3	-1.68	0	0	0.8	0.54	1.48
4	0	0	0	0.51	0.65	0.78
5	0	-1.68	0	0.59	0.83	0.89
6	0	0	0	0.57	0.71	0.80
7	1	-1	-1	1.18	1.32	1.15
8	0	1.68	0	0.38	1.43	0.26
9	1.68	0	0	1.26	1.55	0.81
10	1	-1	1	0.67	0.62	1.08
11	0	0	1.68	0.55	0.49	1.12
12	1	1	1	1.02	1.13	1.25
13	0	0	0	0.53	0.61	0.87
14	-1	-1	-1	1.58	0.42	3.06
15	0	0	-1.68	1.52	0.56	2.71
16	0	0	0	0.51	0.66	0.77
17	0	0	0	0.55	0.63	0.87
18	-1	1	-1	0.69	0.41	1.79
19	-1	1	1	0.31	0.96	0.32
20	1	1	-1	0.93	1.5	0.62

3.3 Empirical equation for height of laser cladding layer

ANOVA method is adopted to analyzing dimension measurement for cross section of laser cladding

layer. The analyzing results are shown in table 3.

Table 3 ANOVA for height of the laser cladding layer

Object	Total variance	Degree of freedom	Average variance	F value	Probability of P value > F value
Model	2.58	9	0.29	97.16	< 0.0001 Significant
Laser power A	0.18	1	0.18	61.45	< 0.0001 Significant
Scanning speed B	0.11	1	0.11	38.97	< 0.0001 Significant
Feeding rate C	0.94	1	0.94	320.04	< 0.0001 Significant
AB	0.15	1	0.15	51.26	< 0.0001 Significant
AC	0.16	1	0.16	53.14	< 0.0001 Significant
BC	0.24	1	0.24	80.67	< 0.0001 Significant

A ²	0.41	1	0.41	138.06	< 0.0001	Significant
B ²	8.69×10 ⁻⁰³	1	8.69×10 ⁻⁰³	2.94	0.117	Insignificant
C ²	0.42	1	0.42	140.98	< 0.0001	Significant
Residual error	0.03	10	2.95×10 ⁻⁰³			
Lack of fit	0.024	5	4.84×10 ⁻⁰³	4.53	0.0614	Insignificant
Pure error	5.33×10 ⁻⁰³	5	1.07×10 ⁻⁰³			
Cor total	2.61	19				
Standard deviation	0.054		R-squared	0.9887		
Mean	0.76		Adjusted R-squared	0.9785		
Coefficient of variation (%)	7.17		Predicted R-squared	0.9243		
PRESS	0.2		Adequate precision	32.919		

The F value of the model is 97.16 and P value less than 0.0001, which indicates that the fitting equation is significant and the fitting degree is high. In this case, it can be seen that laser power (A), laser scanning speed (B) and feeding powder rate (C), interaction parts of AB, AC and BC, second-order parts of A² and C² are all significant factors of height of laser cladding layer. The second-order of B² has the least effect on the height of laser cladding layer, while feeding powder rate (C) is the most effect.

An R-squared is mainly used to explore the fitting effect between the established empirical model and measured results. An R-squared of 0.9887 indicates that there is a high correlation between the experimental results and the measured results of the cladding grinding layer height. The predicted R-squared (0.9243) was not significantly different from the adjusted R-squared (0.9785) in a reasonable degree. And adequate precision of height of laser cladding layer is 32.919, which is acceptable when the ratio is greater than 4, also indicating a high fitting between the experimental results and predicted empirical model.

The empirical fitting model of the cladding grinding layer based on the experimental data measured in this experiment is reasonable. After deleting irrelevant factors, the fitting equation of the empirical relationship between the height of the cladding grinding layer and laser power, laser scanning speed and powder feeding rate can be written as follows:

$$H = 0.54393 + 0.11523P - 0.091762S - 0.26297F + 0.13750PS + 0.14PF + 0.1725SF + 0.16814P^2 - 0.02455S^2 + 0.1699F^2 \quad (4)$$

Figure 4(a) shows the fitting plot based on measured data of laser cladding layer height. A disturbance diagram is shown in Fig. 4(b), which is used to compare the influence of curve changes of various laser processing parameters passing through the center point of the design domain on the height of the cladding grinding layer. It can be seen that the height of the cladding grinding layer increases with the increase of the powder feeding rate, and there is a positive correlation between the layer height and the powder feeding rate. This is because when the powder feeding rate is increased, the amount of powder per unit time in the laser cladding process will be increases, so the amount of powder in the cladding area will increase. In this case, more powder absorb energy in the cladding area base pool interacting with each other, and then form a higher cladding layer. It can also be seen that when the laser power increases, the cladding grinding height will be increased, and there is a positive correlation. This is because energy increase per unit time leading to melting powder increasing.

Fig. 4 (a) Fitting plot and (b) perturbation plot for height of laser cladding layer

Figure 5 shows that interactive effect between laser power and scanning speed on the height of laser cladding layer when feeding rate is constant at 0 point. When the laser scanning speed is fixed and the laser power is increased, the height of the cladding grinding layer can be increased. However,

when the laser scanning speed is increased under the action of high laser power, the change of the cladding grinding layer is not great. Fig. 5(b) shows the contour diagram of the influence of the grinding layer height on the interaction between laser power and powder feeding rate when the laser scanning speed is at the level of 0. These two parameters are positively correlated to the laser cladding grinding layer, so the maximum height of the cladding grinding layer can be achieved by increasing the laser power and powder feeding rate together. When the laser power and powder feeding rate are reduced simultaneously, the height of the cladding grinding layer will be reduced to the minimum.

Fig. 5 Contour plot of effects of (a) AB and (b) AC on height of the laser cladding layer

3.4 Empirical equation for width of laser cladding layer

It can be seen that table 4 that the F value of the fitting model is very high (84.85) and P value is very small (< 0.0001). The adequate precision is 28.925 which the fitting degree is much greater than 4, and the R-squared is 0.9871, which is very close to 1. All the above data show that the experimental measured values fit well with the empirical fitting model. It can also be seen from the table 4 that the laser power, scanning speed the two-factor interaction AB, AC, BC and the second-order interaction of A^2 , B^2 and C^2 are all significantly correlated. According to the analysis of F value, the width of grinding layer is most affected by laser power and least affected by powder feeding rate.

Table 4 ANOVA for width of the laser cladding layer

Object	Total variance	Degree of freedom	Average variance	F value	Probability of P value > F value	
Model	2.49	9	0.28	84.85	< 0.0001	Significant
Laser power A	1.03	1	1.03	317.23	< 0.0001	Significant
Scanning speed B	0.27	1	0.27	83.56	< 0.0001	Significant
Feeding rate C	8.35×10^{-03}	1	8.35×10^{-03}	2.56	0.1406	Insignificant
AB	0.026	1	0.026	8.11	0.0173	Significant
AC	0.46	1	0.46	141.31	< 0.0001	Significant
BC	0.042	1	0.042	12.9	0.0049	Significant
A ²	0.24	1	0.24	73.25	< 0.0001	Significant
B ²	0.36	1	0.36	111.44	< 0.0001	Significant
C ²	0.044	1	0.044	13.42	0.0044	Significant
Residual error	0.033	10	3.26×10^{-03}			
Lack of fit	0.023	5	4.62×10^{-03}	2.42	0.1771	Insignificant
Pure error	9.53×10^{-03}	5	1.91×10^{-03}			
Cor total	2.52	19				
Standard deviation	0.057		R-squared	0.9871		
Mean	0.82		Adjusted R-squared	0.9754		
Coefficient of variation (%)	6.94		Predicted R-squared	0.9246		
PRESS	0.19		Adequate precision	28.925		

After deleting irrelevant factors, the fitting formula of the empirical relationship between the width of the cladding grinding layer can be written:

$$W = 0.66428 + 0.27522P + 0.14125S - 0.024729F + 0.0575PS - 0.24PF + 0.0725SF + 0.12874P^2 + 0.1588S^2 - 0.055103F^2 \quad (5)$$

It can be seen from Fig. 6(a) that the validity of the prediction model for the grinding layer width of cladding can be calculated from the images made by formula (5) and experimental measurement data.

It can be seen from table 4 that laser power has the greatest influence on width of laser cladding layer.

Fig. 6(b) shows a disturbance diagram of the influence of laser processing parameters on the grinding layer width, the disturbance is used to compare the influence of the curve of each laser processing parameters passing through the center point of the domain on the width of laser cladding layer. It can be seen that the width of the laser cladding layer is positively correlated with the laser power, and the width of the cladding grinding layer increases with the increase of the laser power. The reason for this

phenomenon may be that when the laser power increases, the metal substrate receives more laser power, which leads to a wider molten pool width of the metal substrate. Therefore, a wider molten pool can receive more cladding $B_4C/CBN/CuSnTi$ powder to accumulate in the molten pool, and finally leads to a wider layer width. However, the increase of laser scanning speed and powder feeding rate will decrease the width of the cladding grinding layer, and the laser scanning speed and powder feeding rate are negatively correlated with the width of the cladding grinding layer, shown in Fig. 6(b). The reason of negative relation between width of laser cladding layer and scanning speed is that when the laser scanning speed increases, the average power of the laser will decrease, so that the substrate will receive less heat, resulting in the narrow width of molten pool, which leads to the less powder in the molten pool, and eventually narrow width of laser cladding layers are formed. The reason of feeding powder rate increasing leading to width laser cladding layer decreased is that the laser energy reaching to the substrate was reduced by flying high density powder from powder nozzles to the substrate. In this case, the height of the laser cladding layer will be increased, while the width of the grinding layer becomes narrower.

Fig. 6 (a) Fitting plot and (b) perturbation plot for width of laser cladding layer

Fig. 7(a) shows the contour diagram of the influence of laser power and laser scanning speed on the grinding layer width of cladding when the rotary speed is at 0 level. When both laser power and

laser scanning speed increase, the width of the cladding grinding layer is more affected by the laser power, and the width of the cladding grinding layer increases gradually. This phenomenon is consistent with reflected condition of table 4, which shows that the F value of laser power is the maximum 317.23. However, when the laser power is the maximum and the laser scanning speed is the minimum, the width of the cladding layer can reach the maximum. Fig. 7(b) shows contour diagram for laser cladding layer width changing, which is interactively influenced by laser power and feeding powder rate. Fig. 7(b) is similar to Fig. 7(a), when the laser power is the maximum and the rotary speed is the minimum, the width of the cladding grinding layer can reach the maximum. However, the difference between Fig. 7(a) and (b) is that when the laser power is fixed and the powder feeding rate increases or decreases, the change rate of the laser cladding layer width will be larger than that of the laser scanning speed changing. This phenomenon can also be illustrated by the F value of laser scanning speed and the F value of powder feeding rate in table 4.

Fig. 7 Contour plot of effects of (a) AB and (b) AC on width of the laser cladding layer

3.5 Empirical equation for height-width ratio of laser cladding layer

It can be seen from ANOVA analysis of height and weight ratio of laser cladding layer in table 5. F values of all parameters are very high and P values are very small. The F values of powder feeding rate

is the greatest, which is 730.61. The F value for the influence of interaction between laser power and powder feeding rate on the H/W ratio is ranked after that of powder feeding rate, and the value is 688.72. This indicates that the laser cladding processing parameters (whether single factor, interaction factor or second-order factor) are significantly correlated with the aspect ratio of the laser cladding layer. In addition, the value of the R-squared is 0.9961, which is close to 1. The value of the predicted R-squared is 0.9745, which is close to the value of the adjusted R-squared (0.9926), and the value of the Adequate precision is 65.418, which is far greater than the value of 4. All these data indicate that the experimental observation data of the aspect ratio of the cladding grinding layer fit well with the empirical model.

Table 5 ANOVA for H/W ratio of the laser cladding layer

Object	Total variance	Degree of freedom	Average variance	F value	Probability of P value > F value	
Model	9.47	9	1.05	285.3	< 0.0001	Significant
Laser power A	0.57	1	0.57	153.24	< 0.0001	Significant
Scanning speed B	0.64	1	0.64	172.89	< 0.0001	Significant
Feeding rate C	2.69	1	2.69	730.61	< 0.0001	Significant
AB	0.17	1	0.17	46.19	< 0.0001	Significant
AC	2.54	1	2.54	688.72	< 0.0001	Significant
BC	0.37	1	0.37	99.62	< 0.0001	Significant
A ²	0.19	1	0.19	51.09	< 0.0001	Significant
B ²	0.11	1	0.11	28.83	0.0003	Significant
C ²	2.16	1	2.16	585.21	< 0.0001	Significant
Residual error	0.037	10	3.69×10 ⁻⁰³			
Lack of fit	0.028	5	5.58×10 ⁻⁰³	3.11	0.1195	Insignificant
Pure error	8.98×10 ⁻⁰³	5	1.80×10 ⁻⁰³			
Cor total	9.51	19				
Standard deviation	0.061		R-squared	0.9961		
Mean	1.1		Adjusted R-squared	0.9926		
Coefficient of variation (%)	5.5		Predicted R-squared	0.9745		
PRESS	0.24		Adequate precision	65.418		

After deleting irrelevant factors, the fitting formula among laser power, scanning speed and feeding rate can be written:

$$\frac{H}{W} = 0.82044 - 0.20343P - 0.21608S - 0.4442F + 0.14593PS + 0.56349PF + 0.21431SF + 0.11435P^2 - 0.085902S^2 + 0.387F^2 \quad (6)$$

Figure 8 shows a disturbance diagram, which is used to compare the influence of curve changes of various laser machining parameters passing through the center point (0 level) of the design domain on the height/width ratio of the cladding layer. When the laser power is increased, the H/W ratio of the cladding grinding layer decreases gradually, the increase of laser power leads to the expansion of the molten pool width of the metal substrate, which is larger than the increase in height. In this case, although the height and width of the cladding grinding layer increase, the width of the cladding grinding layer increases faster. Increasing the laser scanning speed resulted in less metal powder entering the substrate in unit time and resulted in a thinner cladding grinding layer. In this case, the molten pool of the metal substrate is smaller, and less $B_4C/CBN/CuSnTi$ powder can be collected in the molten pool, which leads to less powder aggregation and melting, resulting in the height of the cladding grinding layer decreasing more rapidly than the width of the cladding grinding layer. Therefore, with the increase of laser scanning speed, the H/W ratio of the cladding grinding layer decreases. When the speed of feeding rate increases, more $B_4C/CBN/CuSnTi$ powders are blown into the molten pool per unit time. As a large number of powders weaken the irradiation effect of laser energy, the powders will be melt more in width direction of melt pool on substrate than that of accumulating in height direction. As the result, the H/W ratio decreases gradually.

Fig. 8 (a) Fitting plot and (b) perturbation plot for H/W ratio of laser cladding layer

Figure 9(a) shows the contour diagram of the influence of laser power and laser scanning speed on the H/W ratio of cladding grinding when the rotary speed is at 0 level. It can be seen from figure 9(a) that when laser power and laser scanning speed decrease simultaneously, the H/W ratio of the cladding layer reaches the maximum. When both increasing laser power and laser scanning speed at the same time, the H/W ratio of the cladding layer can be smaller. And this state is the best for laser cladding layer. However, when the laser power reaches the maximum. The increasing tendency of the H/W ratio slows down, which may be caused by the fact that laser power is large enough to make the dimension of molten pool enlarged, more space are needed to be filled by laser cladding powders.

Figure 9(b) shows the contour diagram of the interactive influence of laser power and feeding rate on H/W ratio of laser cladding layer when the laser scanning speed is at the level of 0. When the laser power and feeding rate are reduced at the same time, the H/W ratio of laser cladding layer can reach the maximum. Therefore, when the laser cladding is processed, the parameters of high laser power, high scanning speed and high feeding rate can be selected as far as possible to get the more appropriate cladding grinding layer.

Fig. 9 Contour plot of effects of (a) AB and (b) AC on ratio to H/W ratio of laser cladding layer

3.6 Laser cladding processing parameters calculating

According to the formula [24] (7), the laser cladding process parameters of laser power, laser scanning speed and feeding rate can be optimized at the same time. The formula can satisfy all the parameters in the research range, and the ultimate goal needs to satisfy the maximum laser cladding layer height, maximum laser cladding layer width, and minimum laser cladding layer H/W ratio.

$$D = [\prod_{i=1}^N d_i^{r_i}]^{1/\sum r_i} \quad (7)$$

N is the response number, r_i represents the importance of correlated response and d_i is specific response coefficient.

4 Optimization for grinding structure of laser cladding grinding layer

4.1 Archimedes helix theory

The polar coordinate formula of Archimedes helix is:

$$r = a + b\theta \quad (8)$$

Where a and b are the factors, θ is the independent variable, r is the dependent variable, and figure 10 shows the Archimedes helix in the polar coordinate system when the coefficient a is 0.

Fig. 10 Archimedean spiral under polar coordinate

4.2 Airflow field and pressure field model for Archimedes helix grinding structure

As the width of laser cladding grinding layer is 1.1mm because of the dimension of laser beam, it is necessary to restrict the pitch between each two Archimedes spirals to be greater than 1.1mm in order to prevent overlapping among laser cladding layers. In this study, three model parameters of laser cladding grinding structure are defined, as the outer diameter R of grinding tool has been determined. These three parameters are the inner circle diameter of grinding tool r which deciding the starting point for laser cladding grinding layers on grinding tool substrate, the shape coefficient β of Archimedes spiral, and the number of Archimedes spiral grinding layers on LCTGT substrate n . The model of Archimedes helix under different coefficients was established by SOLIDWORKS2015 software.

First, the range of shape coefficient β of Archimedes helix should be determined. The length of laser cladding layers are not changed much when β changes from 20 to 30. As longer laser cladding layer can perform better grinding effect, it is better for laser cladding layer to get the length as long as possible excluding mutual interference of two laser cladding layers. In this case, these three parameters need to be determined after comprehensive analysis of simulated grinding performance.

In this section, two parts of simulation analysis were conducted: first is the changes of velocity field and pressure field of non-grinding zone were simulated and analyzed by FLUENT software in various grinding speed with different structural coefficients of laser cladding grinding layers. The second is motion trajectory of laser cladding grinding layers were analyzed by SOLIDWORKS2018 motion module under different structural laser cladding grinding layers at different grinding speeds and feeding speeds.

According to the requirements of simulation, in this paper, five groups of structure of laser cladding grinding layers were selected. Figure 11 shows the structural parameters of these 5 groups of laser cladding grinding layers on the left corner. These structural parameters of each laser cladding layers

are structural coefficient of laser cladding layer β – the number of laser cladding layers n – inner diameter of grinding tool r shown in table 6. The morphology of laser cladding layers are changed by changing Archimedes spiral coefficient β , number of laser cladding layers n and inner diameter of grinding tool r . These structural laser cladding layers mentioned above need to be analyzed by simulation under various grinding parameters (feeding speed and rotating speed) to choose a better structure for producing LCTGTs. The selected simulation grinding tool rotating parameters were shown in Table 7.

Table 6 Parameters of structured grinding wheel

Order	Structural coefficient β	Number of laser cladding layer n	Inner diameter of grinding tool r
1	3	5	6
2	4	6	8
3	5	6	8
4	6	10	10
5	6	10	10

Fig. 11 Different morphologies under different structural parameters

Table 7 Rotation speed for grinding wheel rotating

Rotating speed (rpm)	2000	3000	4000
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Figure 12 shows 3-5-6 structural laser cladding grinding layer under 2000 rpm, it can be seen that the distribution of air flow field and pressure field in the each non-grinding zone of the grinding tool is very uneven. The flow rate at the outlet reaches 3.9×10^4 m/s and the pressure exceeds 3×10^8 Pa. From Fig. 13, it can be seen that there is a strong eddy in the non-grinding zone in the center of grinding tool, which is also not conducive to the grinding efficiency and safety in high grinding speed. In this case, as the air flow and pressure on one side of grinding tool are too high, which leads to the instability of grinding tool and bouncing off during grinding. The dynamic balance of grinding tool cannot be guaranteed, which is extremely unsafe in grinding process. Therefore, such structural parameters for grinding tools are not desirable.

Fig. 12 Velocity magnitude and dynamic pressure for 3-5-6 structured grinding wheel under 2000 rpm

Fig. 13 Local velocity vector plot of 3-5-6 structured grinding wheel center under 2000 rpm

Figure 14 shows the air flow field and pressure field dynamic vector conditions on 5-6-8 type of LCTGT when rotating speeds are 2000rpm, 3000rpm and 4000rpm. On air flow field perspective, when the speed of grinding wheel reaches 2000rpm, the distribution of air flow field in each non-grinding zone of LCTGT is more uniform, which is suitable for LCTGT grinding process. The maximum air flow rate can reach $6 \times 10^3 \text{ m/s}$ with little difference in the distribution of air flow field in each non-grinding zone. As can be seen from figure 14(a) and (d), at the end of non-grinding zone outlet of LCTGT, the far side of the laser cladding grinding layer, there is negative pressure, and the air flow cannot flow out from this point, but flows out from the back tip of each laser cladding layer. In this case, the chips on the workpiece removed by LCTGT in the grinding process flow out along the inside non - grinding channel of LCTGT, and fly away at a certain speed from the back tip of the laser cladding grinding layer. There is no strong vortex in the air flow field and pressure field at the center of the grinding tool at this speed, which is beneficial to the stable grinding.

However, when rotating speed of LCTGT increases to 3000 rpm or above, as shown in figure 14(b), (c), (e) and (f), the distribution of air flow field in non – grinding zone of LCTGT appears uneven. Also, there are symmetrical high air flow velocity on both sides of non – grinding zone of LCTGT higher than that of other non – grinding region. When this phenomenon occurs, the grinding tool will get to the unstable state. In this state, the grinding tool cannot guarantee the dynamic balance of its own rotation. Therefore, LCTGT with the 5-6-8 type structural laser cladding grinding layer cannot be guaranteed when the speed is equal or above 3000 rpm.

Fig. 14 Velocity vector and dynamic pressure vector on 5-6-8 type of LCTGT under 2000, 3000 and 4000 rpm rotating speed.

Figure 15 shows vector diagram of air flow field and pressure field of LCTGT with 6-10-10 type of laser cladding grinding layer under 2000 rpm, 3000 rpm and 4000 rpm. It can be seen that the air flow field and pressure field at 2000 rpm, 3000 rpm and 4000 rpm are evenly distributed in each non-grinding zone. When the speed value reaches 4000 rpm, although the air flow field and pressure field are high, they are still evenly distributed in the grinding tool, which is not found in the previous several types of structural laser cladding grinding layers, proving that 6-10-10 type of LCTGT is suitable for high-speed grinding environment.

And also, it is difficult to see that there is serious eddy current at the inner center of LCTGT. The reason for this phenomenon may be that when the inner diameter is expanded to 10 mm, the internal space is improved, which alleviates the vortex phenomenon caused by the air collision caused by overcrowding when the air flow moves. In this way, the air flow inside the grinding tool is smoother and the grinding tool can rotate at a higher speed.

Fig. 15 velocity vector(a)(b)(c) and dynamic pressure(d)(e)(f) of 6-10-10 structured grinding wheel under 2000rpm, 3000rpm, 4000rpm

4.3 Grinding trajectory analyzing for LCTGT model

There is a similar linear relationship between the number of abrasive particles and the length of the laser cladding grinding layer analyzed by statistical method, shown in figure 16. It can be seen that, when the length of the laser cladding layer is increased by 1mm, the number of abrasive particles will increase by 6. According to the formula of Archimedes spiral length in polar coordinates, the length of each grinding layer can be calculated as follows:

$$s = \alpha \int_{\theta_1}^{\theta_2} \sqrt{1 + \theta^2} d\theta \quad (9)$$

In this function, θ_1 is the starting angle and θ_2 is the terminating angle. Through calculation, the number of abrasive of each type of structural laser cladding grinding layer can be obtained, shown in table 8.

Fig. 16 Fitted plot for grains and laser cladding grinding layer length

Table 8 Grain numbers on single layer with various types of laser cladding grinding layer

Type of structural laser cladding grinding layer	Length (mm)	Number (N)
3-5-6	38.27	230
4-6-8	29.91	180
5-6-8	25.09	160
6-10-6	22.02	140
6-10-10	19.61	120

In this paper, grinding trajectory of different types of structural laser cladding grinding layers are simulated by SOLIDWORKS2018 motion module. As the number of abrasive on single laser cladding grinding layer is large, the trajectory of a single abrasive on laser cladding grinding layer cannot be distinguished in high rotating and feeding speed of LCTGT. Therefore, in order to simplifying the observation of abrasive motion trajectory on various types of single laser cladding grinding layer, 10 abrasive on laser cladding grinding layer as 1 trajectory generation point in the motion simulation process. The moving parameters of simulated laser cladding grinding layers are shown in table 9, 4 groups of parameters were obtained by combining the rotating speed and feeding speed of LCTGT.

Table 9 Simulation process parameters of structured grinding tracks

Parameters	Rotating speed (rpm)	Feeding speed (mm/min)
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Parameters 1	2000	10
Parameters 2	4000	30

Figure 17 shows (a) grinding trajectory at 2000 rpm with a feeding speed of 10 mm/min, (b) 2000 rpm with a feeding speed of 30 mm/min, (c) 4000 rpm with a feeding speed of 10 mm/min and (d) 4000 rpm with a feeding speed of 30 mm/min of moving parameters for 3-5-6 type of laser cladding layer for LCTGT. It can be found that the shape of trajectory is affected by the rotating speed and feeding speed of laser cladding grinding layer for LCTGT. There are two more dense lines in the middle, which is the beginning of the cladding grinding layer from the center of the grinding tool. And the grinding trajectory in the process of running appeared condition of stratification. As can be seen from figure 17, when the feeding speed of LCTGT is 10 mm/min. The density of abrasive moving trajectory of LCTGT with rotating speed of 4000 rpm is higher than that of 2000 rpm. And also, when the feeding speed is 30 mm/min, the density of abrasive moving trajectory of LCTGT with rotating speed of 4000 rpm is higher than that of 2000 rpm.

Fig. 17 Grinding tracks from single grinding layer under different process parameters using 3-5-6 structured grinding wheel

Figure 18 shows the trajectory diagram of structural type of 5-6-8 for LCTGT with (a) rotating speed of 2000 rpm and feeding speed of 10 mm/min, (b) rotating speed of 2000 rpm and feeding speed of 30 mm/min, (c) rotating speed of 4000 rpm and feeding speed of 10 mm/min, (d) rotating speed of 4000 rpm and feeding speed of 30 mm/min. When the feeding speed is 10 mm/min, it can be seen that the density of abrasive trajectory does not change and relatively uniform in the non-dense area of grinding tool trajectory comparing with trajectory diagram of 2000 rpm and 4000 rpm. In the dense area of abrasive trajectory, the density of trajectory for 4000 rpm LCTGT is higher than that of 2000 rpm. When LCTGT moves at high feeding speed, 30 mm/min, it is not obvious for the density of non-dense area of abrasive trajectory changing comparing with rotating speed of 2000 rpm and 4000 rpm of LCTGT, while, in the dense area, it is more density and uniform for LCTGT moving trajectory with rotating speed of 4000 rpm than that of 2000 rpm. And it can be found that the dense area covers a large area under rotating speed of 2000 rpm. From the grinding trajectory diagram of structural type of 5-6-8 for LCTGT, it can be seen that the workpiece quality can be achieved at the side close to outer circle of grinding with slow feed and high rotating speed.

Fig. 18 Grinding tracks from single grinding layer under different process parameters using 5-6-8 structured grinding wheel

Figure 19 shows diagram of abrasive trajectory of the type of 6-10-10 LCTGT with (a) rotating speed of 2000 rpm with feeding speed of 10 mm/min, (b) 2000 rpm with feeding speed of 30 mm/min, (c) 4000 rpm with feeding speed of 10 mm/min and (d) 4000 rpm with feeding speed of 30 mm/min. Compared with figure 19(a) and (b) when the grinding tool feeding speed was 10 mm/min, the density of trajectory does not change significantly, the trajectories are very uniform. The comparison between figure 19(b) and (d) shows that when the feeding speed of LCTGT is 30 mm/min, the changes of the trajectory density zone is not obvious, and the center of grinding trajectories is more uniform when rotating speed is 4000 rpm. On the outside of the LCTGT, the change is also uniform.

Comparing figure 17 with figure 19, it can be found that the smaller coefficient β is, the more intensive density of the grinding trajectory is, and it is the main factor that affects the shape of the grinding trajectory. However, when the coefficient β is too small, there will be non-uniformity of grinding trajectory, and a large number of obviously different grinding density areas will appear in the grinding

region of grinding tool. In this case, it is not conducive to guarantee the quality of the grinding workpiece.

This phenomenon will be gradually alleviated by the increase of coefficient β . When coefficient β is 6, the grinding density zone will become very narrow, while the grinding areas are uninform. Stratification of grinding trajectory can be reduced with better quality of workpiece under uniform surface roughness.

Fig. 19 Grinding tracks from single grinding layer under different process parameters using 6-10-10 structured grinding wheel

According to the adjustment, selection, simulation and analysis for processing parameters of LCTGT mentioned above, when the coefficient β is 6, the number of laser cladding grinding layers is 10 and the inner diameter of LCTGT is 10mm, the distance between two laser cladding grinding layers is greater than 1.1 mm. In this case, the range of rotating speed of LCTGT is large and grinding condition is stable under high speed. Therefore, type of 6-10-10 of laser cladding grinding layer can be selected as the structural parameters for LCTGT grinding layers.

5 Preparation for LCTGT

It is a key step to generate the laser cladding grinding layer trajectory file and import it into KUKA robot controller. In this paper, Solidworks 2018 is the three-dimensional model established software. According to the shape and size of the grinding tools substrate end face, 6-10-10 type 3D model for textured laser cladding grinding structure is established. The model mentioned ahead is saved with IGS format.

After that, the IGS format of the 3D parts was imported into Robotart-2018 software. In the course of trajectory design, optimization, and output using Robotart-2018 software, the following steps are required: Firstly, select and load the robot model of KUKA16-2 and IPG laser head as 3d parts. Second, set up TCP points and measure parts. Third, design and optimize the trajectory of laser moving beam. Fourth, detect and adjust the collision for KUKA 16-2 and IPG laser head during processing in the software with a simulation. Fifth, the laser head moving trajectory is derived and saved with identifiable program for KUKA 16-2 control system.

The designing and optimizing of the trajectory with software like Robotart-2018 greatly affect the quality of the laser cladding grinding layer, such as temperature gradient, thermal stress, surface tension, internal microstructure, porosity or crack appearance. Through reasonable design and optimization of the trajectory for laser cladding head, the quality of the laser cladding grinding layer can be improved, and the efficiency of the preparation can be improved.

Figure 20 shows the designing environment in the Robotart-2018 software, and figure 20(a) shows the robot arm, laser head and workpiece in the simulation environment. In this environment, the previously generated workpiece IGS format files are imported into the Robotart-2018 software, and the movement track of laser head and mechanical arm is generated on the parts. After the trajectory being

generated, it is necessary to optimize the trajectory of the laser head and the robotic arm: First is to fix the Z-axis of laser head to ensure that the laser head and arms cannot rotate arbitrarily during laser cladding. The second step is to determine the step length of the laser head and robotic arm movement. When the moving step size decreases, the real laser cladding trajectory will have a higher fitness with the designed trajectory during laser cladding process. In other words, when the step size of each step decreases, the designed trajectory will be more accurate. The third step, choose the laser cladding starting point and end point. When selecting the starting point and ending point of the laser head, the position of the laser light on and off will also be considered. The operation of structure of LCTGTs is carried out by controlling laser on and off and cooperation with powder feeding from coaxial powder feeding outlets on laser head. The fourth step is to optimize laser cladding process trajectory. The purpose of trajectory optimization is to adjust the relevant position of the laser head. The laser head in this experiment needs to droop naturally and be perpendicular to the working plane. In this case, the safety of laser cladding can be ensured, and laser head can be fixed during laser cladding process while laser head moving. The arbitrary movement with swing action of laser head is inhibited during laser cladding process, then the accuracy of laser cladding layer can be improved. Finally, the designed and optimized trajectory of the laser cladding grinding layer is transformed into a machine language that can be recognized by KUKA 16-2 robot control system. The files are imported into KUKA robot control system, and the processing experiments are carried out by controlling the KUKA 16-2 robot.

Fig. 20 (a) KUKA robot arm, laser head and (b) dot matrix of laser motion tracks

When the well-designed and optimized laser cladding orbit running files are imported to the KUKA robot, the processing experiment of laser cladding textured grinding wheel can be carried out. The powder is added into powder feeding barrel, the parameters of laser processing are set, and then laser cladding experiment can be carried out by KUKA robot controller. First, grinding tool substrate under the laser cladding head should be placed and the distance between the laser head should be adjusted. The distance between the laser head and the grinding tool substrate is 15mm. Second, grinding structure of LCTGT is carried out by controlling Robot moving based on imported laser cladding track file. Third, the fabrication of LCTGT is completed, grinding structure on LCTGT substrate end face is shown in figure 21.

Fig. 21 Laser cladding textured grinding tool

Conclusions

(1) RSM method was used to analyze the relationship between the morphology of laser cladding layer (height, width and height/width ratio) and laser cladding process parameters (laser power, laser scanning speed and powder feeding rate), and the laser processing parameters were optimized by multi-objective. The height of laser cladding layer is mainly related to the powder feeding speed of grinding tool. The width of the laser cladding layer is mainly related to the laser power. The H/W ratio of laser cladding layer is mainly related to the power feeding rate. Through multi-objective optimization, the optimal laser processing parameters are 397W of laser power, 3.56 mm/s of the laser scanning speed and 0.91 r/min of powder feeding rate.

(2) The macro structural laser cladding grinding layers were optimized. When the rotating speed is 2000 rpm, the air flow and air pressure of the non-grinding area for structural type 3-5-6 of laser cladding layer appears instable. On the other side, the air flow and air pressure of the structural type 6-10-10 laser cladding grinding layer in non-grinding zone are stable under rotating speed of 4000 rpm. And also the coverage area of abrasive trajectory for structural type 6-10-10 laser cladding layer is more uniform and dense than of other structural type for LCTGT. In this case, structural type of 6-10-10 is

suitable for LCTGT producing.

(3) LCTGT was fabricated in laboratory. The laser cladding process trajectory was designed and optimized by software. And with the cooperation of KUKA robot arm, LCTGT can be produced.

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Declarations

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b. Conflicts of interest

Not applicable.

c. Availability of data and material

The authors declare that the data and material supporting the findings of this work are available within the article

d. Code availability

Not applicable.

e. Ethics approval

Not applicable..

f. Consent to participate

Not applicable.

g. Consent for publication

Not applicable.

h. Authors' contributions

Xufeng Zhao: research grinding and precession machining.

Changhe Li: research grinding and precession machining, high speed and ultra-high speed machining and digitalized manufacturing.

Tianbiao Yu: research grinding and precession machining, digital design and intelligent manufacturing, Additive manufacturing and 3D printing and green remanufacturing.

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