Laser additive remanufacturing parameters optimization and experimental study of heavy-duty sprocket

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Abstract
Experimental research on laser additive remanufacturing technology of heavy-duty sprocket was carried out. The influences of laser power, scanning speed, and powder feeding rate on cladding height, cladding area, melting area, and dilution rate were compared and analyzed. The prediction models of the combination of process parameters with the geometric characteristics of cladding layer and dilution were established. A multi-objective process parameter optimization model with the maximum cladding height and cladding area, the minimum melting area, and dilution rate as objective functions was established, and the model was optimized and solved based on MOPSO algorithm. The laser additive remanufacturing repairing experiment of damaged sprocket was carried out by using the optimal parameter combination, and the microstructure and mechanical properties of the repaired region were analyzed. The results show that the scanning speed and powder feeding rate are the main factors influencing the geometric characteristics and dilution of the cladding area, and the models have good prediction accuracy. The optimal process parameters (1150 W, 950 mm/min, 3.8 rad/min) obtained by MOPSO algorithm are adopted to repair the damaged sprocket. The repaired area without cracks and pores and the cladding layer show good metallurgical bonding with the substrate, and the microhardness is twice that of the substrate. The experimental results prove that the laser additive remanufacturing technology is feasible to repair the damaged heavy-duty sprocket and has a strong engineering application prospect.

Keywords Laser additive remanufacturing · Heavy-duty sprocket · Cladding · MOPSO algorithm · Parameters optimization

1 Introduction
Heavy-load sprocket is a significant component of power transmission for fully mechanized mining equipment. In the process of coal mining and transportation, the working conditions are harsh. The sprocket bears not only static load but also pulsating and impact load. The longtime engagement between the sprocket tooth nest and the chain causes severe wear of the tooth nest, the power transfer efficiency of fully mechanized mining equipment decreases, and the dynamic reliability and service life of the whole machine are significantly reduced. The research on remanufacturing and repairing technology of damaged sprocket has become the focus of manufacturing and operation maintenance service enterprises of fully mechanized mining equipment.

Many scholars have carried out a number of researches on remanufacturing and repair technology, such as brushing electroplating [1], arc welding [2], thermal spraying [3], hardfacing [4], and plasma spraying [5]. However, these methods have many weaknesses that are not conducive to the quality control of mechanical parts repair, such as large heat-affected zone, uneven thermal stress distribution, and poor precision, and the internal crack defects of the repair layer cannot be effectively regulated.

Laser additive remanufacturing technology, as an emerging repair technology, has the characteristics of low dilution rate, less porosity and crack defects, dense structure, rapid solidification, more cleanless, and a good combination of cladding layer and substrate [6–8]. Due to the above significant advantages, laser additive remanufacturing technology has been applied in such important fields as single crystal turbine blades [9], continuous caster lateral rolls [10], hydraulic piston rods [11], and railway rails [12] and has

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achieved remarkable economic benefits. At present, many published works have reported on the research results of laser additive remanufacturing technology. For instance, Song et al. [13] used stainless steel powder as cladding material and adopted laser additive technology to process V-grooves on medium carbon steel substrates. They concluded that the cladding layer had a good fusion bond with the substrate, and the tensile strength, impacting toughness, elongation, and microhardness of the rebuilt regions have been greatly enhanced. Qi et al. [14] proposed a geometry-based adaptive toolpath laser deposition method for the repair of blisk airfoils. The results show that the repair blisk blades have no obvious defects and have good dimensional accuracy. Rottwinkel et al. [9] investigated the crack repair of single crystal turbine blades using laser cladding technology. It could be shown successfully that inductive preheating leads to a crack-free clad, and laser cladding technology can be an efficient method to repair single crystal turbine blades. Ray et al. [10] utilized laser cladding technology to enhance the service life of caster lateral rolls, which significantly improved the wear resistance and corrosion resistance of the side roller. J. Tuominen et al. [11] prepared a laser cladding repair layer on a worn hydraulic piston rod to improve the surface hardness, wear resistance, corrosion resistance, and fatigue strength of the piston rod. Robles et al. [12] put forward a set of laser additive repair technologies, including thermal analysis, heat treatment, numerical simulation, and performance testing, which can increase the rail tracks service life up to 1400% when compared to those of initial state. Xu [15], Penaranda [16], and Stefan et al. [17] successfully applied laser additive remanufacturing technology to the repair process of the blade tip and achieved good repair results. Liu et al. [18] determined the optimal process parameters of sprocket repair according to the low dilution rate. The processing experiment found that the size error of the repaired sprocket is small, the microhardness of the cladding layer is high, and the cladding layer forms metallurgical bonding with the substrate.

In summary, laser additive remanufacturing technology has been proven to be an effective way to achieve successful repairing of mechanical parts [18]. In this paper, the experimental research on laser additive remanufacturing of heavy-load sprocket used in mining was carried out. The effects of process parameters such as laser power $P$, scanning speed $V$, and powder feeding rate $F$ on the geometric characteristics of single clad tracks, such as cladding height $H_C$, cladding zone area $A_C$, fusion zone area $A_{ fus }$, and dilution ratio $D$, are analyzed in detail. The prediction models between process parameters and geometric characteristics of single clad tracks were established as a combined parameter, respectively. A multi-objective process parameter optimization model for laser additive remanufacturing was constructed with the objective function of maximum cladding height $H_C$, the maximum cladding zone area $A_C$, the minimum fusion zone area $A_{ fus }$, and the minimum dilution ratio $D$. The validation experiment of the laser additive remanufacturing of double-row heavy-load sprocket was carried out, and the microstructure and mechanical properties of the repaired sprocket tooth nest were evaluated.

## 2 Experiment and method

### 2.1 Materials and equipment

The whole experimental process was divided into two stages. The first experimental stage was carried out on the AISI 4340 (the same material as the sprocket to be remanufactured) specimen with the structure dimensions of $40 \times 30 \times 20$ mm, which was used to analyze the influences of the process parameters, establish the prediction models, and obtain the optimal process parameters combination. The substrate must first be polished and wiped with alcohol and acetone to remove surface rust, grease, and other stains. A FeCr-based alloy material was adopted as the laser cladding powder in which particle size is $30 \sim 200$ μm. The morphology, the particle size, and the composition of the powder material are shown in Fig. 1 and Table 1, respectively. In order to prevent moisture from affecting powder fluidity, 4 h insulation drying at 80 °C of the powder should be taken before the cladding process.

In the second stage, the heavy-load sprocket was repaired by laser additive remanufacturing using the optimal process parameter combination. The experimental research of laser additive remanufacturing for sprocket was carried out on a four-axis linkage numerical control platform. The workbench can realize 3-axis (X, Y, Z) movement, and the sprocket was clamped on the turntable to achieve rotational motion. A 3000 W fiber-coupled diode laser with a continuous wavelength of 900 ~ 1080 nm was utilized. IWS-COAX8 coaxial powder feeding nozzle and PF2/2 rotary synchronous powder feeder were used for coaxial powder feeding, and the powder carrier and protective high purity argon was adopted to isolate oxidation.

After disposing accomplished all the cladding processing experiments, specimens were subjected to cutting, grinding, polishing, corrosion (C$_2$H$_5$OH: HNO$_3$ = 24:1, vol. %), cleaning, and drying to prepare as analytical samples. The geometric characteristics of each cladding track cross section of the first experimental stage were measured using the optical digital microscope (VHX-5000). The cross section microstructure and the Vickers hardness of remanufactured sprocket were observed and measured by metallographic microscope (ZEISS Axio Scope A1 with magnification from 200 to 500 times) and microhardness tester (Akashi MVK-H11), respectively.
As shown in Fig. 2, the geometric characteristics of single cladding layer usually include cladding height ($H_C$), cladding width ($W_C$), cladding zone area ($A_C$), fusion zone area ($A_{mix}$), cladding depth ($H_{mix}$), and heat-affected zone ($HAZ$). Dilution ratio refers to the degree of material composition changes in the fusion zone caused by the heat fusion of the substrate material during the laser cladding process. If the dilution ratio is too large or too low, the cladding layer will easily delaminate and the expected performance of the cladding layer will decrease. An ideal dilution rate ($2 \sim 10\%$) is the key to cladding layer forming and performance improvement [19]. The calculation method of dilution ratio in this paper is shown in Eq. (1) [20, 21].

$$D = \frac{A_{mix}}{A_{mix} + A_C} \times 100\%$$  \hspace{1cm} (1) 

The geometry is greatly affected by the process parameters [22]. According to the kinds of literature [23–25], laser power ($P$), scanning speed ($V$), and powder feeding rate ($F$) are the most important factors affecting the geometric characteristics of the cladding layer. The detailed orthogonal experimental schemes are listed in Table 2. The geometry parameters, namely cladding height ($H_C$), cladding area ($A_C$), fusion zone area ($A_{mix}$), and dilution ratio ($D$) of cladding cross section, were chosen as evaluation indexes of geometric characteristics of the cladding layer. Table 3 lists the measurement results of the evaluation indexes of the geometric characteristics of the cladding tracks under various process parameters.
2.3 Optimization method

The PSO algorithm [26] randomly initialized swarm \( X = (x_1, x_2, \ldots, x_N) \) in the feasible solution D-dimensional space. The number of particles was \( N \); the position, the velocity, and the optimal position of particle \( i \) were expressed as \( x = (x_1^i, x_2^i, \ldots, x_D^i) \), \( v = (v_1^i, v_2^i, \ldots, v_D^i) \), and \( p_{\text{Best}}^i = (p_1^i, p_2^i, \ldots, p_D^i) \), respectively; and the global optimal position was expressed as \( g_{\text{Best}} = (p_1^g, p_2^g, \ldots, p_D^g) \). For the \( k^{th} \) iteration, the velocity and the position of the D-dimension particle \( i \) were updated by Eq. (2) and Eq. (3).

\[
\begin{align*}
    v_i^d &= \omega v_i^d + c_1 r_1 (p_i^d - x_i^d) + c_2 r_2 (p_{g}^d - x_i^d) \quad (2) \\
    x_i^d &= x_i^d + v_i^d \quad (3)
\end{align*}
\]

where \( 1 \leq i \leq N \), \( \omega \) is the inertial weight factor; \( c_1 \) and \( c_2 \) are the acceleration coefficients; \( r_1 \) and \( r_2 \) are the random numbers obey \( U(0,1) \); \( p_i^d \) and \( p_{g}^d \) are the individual optimal position of the \( i^{th} \) particle and the \( d^{th} \) component of the global optimal position; \( v_i^d \) is the \( d^{th} \) component of the \( i^{th} \) generation particle velocity; and \( v_i^d \in [v_{\text{mind}}, v_{\text{maxd}}] \), taking the boundary value when the particle updating exceeds the boundary.

The MOPSO algorithm is established on the basis of PSO algorithm, which has the advantages of diverse non-inferior solutions, rapid computational efficiency, and solution speed, and has become an effective means to solve multi-objective optimization problems. The MOPSO algorithm is composed of external archive maintenance and global optimal position selection and update, which solves the dominant situation between individuals based on the Pareto relationship and selects the individual and the global optimal position according to the external archive information and crowded distance. In this paper, the MOPSO algorithm was applied to complete the optimization solution of the multi-objective optimization model.

3 Results and discussion

3.1 Analysis of experimental results

Figure 3 shows the influence trend of numerous factors and levels on cladding geometry, which involves cladding height (\( H_C \)), cladding zone area (\( A_C \)), fusion zone area (\( A_{\text{mix}} \)), and dilution ratio (\( D \)). The cladding height (\( H_C \)) presents a trend of first increasing and then decreasing with the increase of laser power \( P \), which can principally be ascribed to the rise in laser irradiation energy absorbed by the molten pool with the addition of laser power, the amount of fusional powder in the molten pool increases, and the cladding height presents a trend of gradually increasing. However, when the laser power exceeds the threshold value, the powder is prone to gasification or even the formation of plasma. The liquid metal in the molten pool fluctuates violently and extends to both sides, resulting in a downward trend of the cladding height. There is a strong linear relationship exhibit between scanning speed (\( V \)) and cladding height (\( H_C \)), which is also reflected in

| No | Laser power \( P \) [W] | Scanning speed \( V \) [mm/min] | Powder feeding rate \( F \) [rad/min] | Cladding height \( H_C \) [mm] | Cladding zone area \( A_C \) [mm²] | Fusion zone area \( A_{\text{mix}} \) [mm²] | Dilution ratio \( D \) [%] |
|----|--------------------------|-------------------------------|-------------------------------------|------------------------------|---------------------------------|---------------------------------|----------------------|
| 1  | 1100                     | 700                           | 2.9                                 | 0.401                        | 0.751                           | 0.094                           | 11.12                |
| 2  | 1100                     | 800                           | 3.2                                 | 0.370                        | 0.740                           | 0.089                           | 10.74                |
| 3  | 1100                     | 900                           | 3.5                                 | 0.364                        | 0.726                           | 0.079                           | 9.81                 |
| 4  | 1100                     | 1000                          | 3.8                                 | 0.357                        | 0.733                           | 0.068                           | 8.49                 |
| 5  | 1200                     | 700                           | 3.2                                 | 0.435                        | 0.850                           | 0.102                           | 10.71                |
| 6  | 1200                     | 800                           | 2.9                                 | 0.353                        | 0.726                           | 0.092                           | 11.25                |
| 7  | 1200                     | 900                           | 3.8                                 | 0.422                        | 0.878                           | 0.083                           | 8.63                 |
| 8  | 1200                     | 1000                          | 3.5                                 | 0.334                        | 0.689                           | 0.073                           | 9.58                 |
| 9  | 1300                     | 700                           | 3.5                                 | 0.456                        | 0.960                           | 0.116                           | 10.78                |
| 10 | 1300                     | 800                           | 3.8                                 | 0.461                        | 0.966                           | 0.097                           | 9.13                 |
| 11 | 1300                     | 900                           | 2.9                                 | 0.336                        | 0.697                           | 0.086                           | 10.98                |
| 12 | 1300                     | 1000                          | 3.2                                 | 0.323                        | 0.641                           | 0.074                           | 10.35                |
| 13 | 1400                     | 700                           | 3.8                                 | 0.489                        | 1.079                           | 0.114                           | 9.56                 |
| 14 | 1400                     | 800                           | 3.5                                 | 0.383                        | 0.813                           | 0.098                           | 10.78                |
| 15 | 1400                     | 900                           | 3.2                                 | 0.360                        | 0.741                           | 0.091                           | 10.94                |
| 16 | 1400                     | 1000                          | 2.9                                 | 0.294                        | 0.511                           | 0.062                           | 10.82                |
the relationship between powder feeding rate ($F$) and cladding height ($H_C$). With the increase of scanning speed ($V$) or the decrease of powder feeding rate ($F$), the laser irradiation energy and powder quantity involved in the reaction decrease, and the cladding height decreases significantly.

As the laser power ($P$) increases, the cladding zone area ($A_C$) also appears to increase first and then decrease (as shown in Fig. 3b) with the same trend as that of cladding height ($H_C$) in Fig. 3a. There is a negative correlation between scanning speed ($V$) and cladding zone area ($A_C$), and the powder feeding rate ($F$) has a positive influence on cladding zone area ($A_C$), which is due to the reduction of the powder feeding rate per unit time with the increase of the scanning speed or the decrease of the powder feeding rate.

From Fig. 3c, the fusion zone area ($A_{mix}$) shows a downward trend after initial rise with the increase of powder feeding rate ($F$). This is since with the increase in the amount of powder entering the laser irradiation zone, the powder absorbs more laser irradiation energy and the substrate material gets insufficient melting, resulting in a declining trend of the cladding fusion zone area after reaching the critical state.

As shown in Fig. 3d, the dilution ratio ($D$) gradually increases with the rise of laser power ($P$) but decreases with the increase of the scanning speed ($V$) and the powder feeding rate ($F$). In the case where the laser power and the scanning speed are constant, the powder feeding rate determines the ratio of the energy absorbed by the powder and the substrate. With the increase of powder feeding rate, the cladding zone area increases, the absorption energy of the substrate decreases, and the fusion zone area is reduced. Cladding zone area and fusion zone area change oppositely, resulting in an obvious phenomenon that the dilution ratio changes with the powder feeding rate.

### 3.2 Prediction model

It is meaningful to set up a prediction model between process parameters and geometric characteristics of cladding layer [7]. As shown in Eq. (4), Cheikh [27] established a prediction model, which can forecast the geometric characteristics of the laser cladding layer through processing parameters.

\[
y = k(P^{\alpha}V^{\beta}F^{\lambda}) + b
\]  

where $y$ is one of the geometry parameters of the cross section, while $k$ and $b$ are constants. $\alpha$, $\beta$, and $\lambda$ are the index of process parameter laser power ($P$), scanning speed ($V$), and powder feed rate ($F$), respectively. The same formula was utilized to predict the interrelation between the process parameters (laser power ($P$), scanning speed ($V$), and powder feeding rate ($F$)) of laser cladding and the geometric parameters [28] of a single laser tracks (cladding height ($H_C$), cladding zone area ($A_C$), fusion zone area ($A_{mix}$), and dilution ratio ($D$)).
(a) Prediction model of $H_C$

$$H_C = 21.77 - 0.0339t - 0.6614F - 0.001t - 0.0784$$

$R^2 = 0.9365$

(b) Residuals of $H_C$

(c) Prediction model of $A_C$

$$A_C = 33.34 - 0.1519t - 0.9189F - 1.1024 + 0.0101$$

$R^2 = 0.9334$

(d) Residuals of $A_C$

(e) Prediction model of $A_{mix}$

$$A_{mix} = 0.259P^{0.3919} - 1.1607F^{-0.2794} + 0.0025$$

$R^2 = 0.9127$

(f) Residuals of $A_{mix}$

(g) Prediction model of $D$

$$D = 21.6P^{0.214} - 0.214F - 0.782 + 0.2758$$

$R^2 = 0.8683$

(h) Residuals of $D$
By calculating, the predicted model of cladding height \((H_C)\) can be calculated by formula \(H_C = 21.77P^{0.0330}V^{0.66}F_{0.6911}^{0.0784}\) with a correlation coefficient \(R^2 = 0.9365\) (as shown in Fig. 4a), and the measured value of the cladding height has a strong correlation with the predicted value. The index of laser power \((P)\) approaches to 0, which indicates that the coefficient of laser power has little effect on the cladding height. The index of the scanning speed \((V)\) is \(-0.6614\), indicating that the scanning speed has a negative influence on the cladding height. The index 0.6911 of powder feeding rate \((F)\) indicates that powder feeding has a positive effect on cladding height. The prediction model calculation results are consistent with the experimental analysis results, and Fig. 4b demonstrates the residuals of the prediction model of cladding height. In this paper, the residual is defined as the difference between the models prediction results and the experimental measurement data.

The predicted model of cladding zone area \((A_C)\) can be calculated by formula \(A_C = 33.34P^{0.1519}V^{0.9189}F_{1.1024}^{1.024} + 0.0101\) with a correlation coefficient \(R^2 = 0.9334\) (as shown in Fig. 4c) which indicates that the predicted model results have a good correlation with the experimental results. Similar to the prediction model of cladding height \((H_C)\), the index 0.1519 of laser power \((P)\) indicates that laser power has a weak effect on cladding zone area. The index of scanning speed \((V)\) and powder feeding rate \((F)\) are \(-0.9189\) and 1.1024, respectively, which indicates they both have a vital effect on cladding zone area. However, the index of scanning speed is a negative number, which means it has a substantial negative impact on cladding zone area. The residual diagram in Fig. 4d verifies the accuracy of the predicted model.

Meanwhile, the fusion zone area \((A_{mix})\) also can be calculated by formula \(A_{mix} = 9.25P^{0.3919}V^{1.1067}F_{0.2794}^{1.1607} + 0.025\) with a correlation coefficient \(R^2 = 0.8663\) (as shown in Fig. 4e). The index of scanning speed \((V)\), laser power \((P)\), and powder feeding rate \((F)\) are \(-1.1067, 0.3919\), and 0.2794, respectively. The index which is more than \(-1\) shows that scanning speed \((V)\) has the most negative effect on the area of fusion zone area. These predictions are also consistent with the analysis in Sect. 2.1. Figure 4f indicates the residuals of the prediction model of fusion zone area.

The predicted model of dilution ratio \((D)\) can be calculated by formula \(D = 21.16P^{0.2214}V^{0.2418}F_{0.7382}^{0.0784} + 0.2758\) with a correlation coefficient \(R^2 = 0.8663\) (as shown in Fig. 4g) and superior residuals (as shown in Fig. 4h). The index of laser power \((P)\) and scanning speed \((V)\) are 0.2214 and \(-0.2418\) respectively, which indicates they both have a slight effect on dilution ratio. The powder feeding rate index reached 0.7382, indicating that the dilution ratio varies obviously with the increase of powder feeding rate, which is consistent with the prediction model fitting results.

### 4 Laser additive remanufacturing of the sprocket

#### 4.1 Processing parameters

There is much sense that a strong intermixture and metallurgical bond with minimum dilution can be provided by laser cladding [22]. Many studies have indicated that the cladding layer of low dilution rate has well microstructure and mechanical properties [22, 29]. As shown in Eq. (5), in order to reduce the energy consumption of the processing process and improve the metallurgical bonding between the substrate and the cladding layer, a multi-objective optimization problem was constructed with maximizing cladding height \((H_C)\), maximizing cladding zone area \((A_C)\), minimizing fusion zone area \((A_{mix})\), and minimizing dilution ratio \((D)\).

\[
\begin{align*}
\text{max} \{ & H_C(P, V, F), A_C(P, V, F) \} \\
\text{min} \{ & A_{mix}(P, V, F), D(P, V, F) \} \\
& 1100 \leq P \leq 1400 \\
& 700 \leq V \leq 1000 \\
& 2.9 \leq F \leq 3.8
\end{align*}
\]

In the solving process of MOPSO, the population size was \(N = 100\), the number of iterations was \(I = 2000\), the maximum inertia weight was \(\omega_{\text{max}} = 0.9\), the minimum inertia weight was \(\omega_{\text{min}} = 0.4\), and the learning factor \(c_1 = c_2 = 2\). The multi-objective model optimization results are shown in Fig. 5 where each point represents an optimal solution in the Pareto frontier solution set.

According to the analysis in Sects. 2.1 and 2.2, the powder feeding rate \((F)\) is the most important factor affecting the dilution ratio \((D)\). As shown in Fig. 5a, when the powder feeding rate \(F = 3.8\) rad/min and the scanning speed \(V = 900 - 950\) mm/min, the dilution ratio and the fusion zone area are minimized, while the cladding height and the cladding zone area reach the maximum. Figure 5b shows that when the laser power \(P = 1150\) W and the scanning speed \(V = 950\) mm/min, the multi-objective optimization model can obtain the maximum cladding height and cladding zone area, as well as the minimum fusion zone area and dilution ratio. Figure 5c clearly demonstrates that the optimal solution obtained via the MOPSO algorithm converges into a smooth Pareto front curve, which indicates that the calculation result is desired. Then the optimal process parameters of sprocket remanufacturing are as follows: laser power \(P = 1150\) W, scanning speed \(V = 950\) mm/min, and powder...
feeding rate \( F = 3.8 \text{ rad/min} \). The sprocket remanufacturing process was studied by using the optimal process parameters in this study.

The experimental setup of laser additive remanufacturing for damaged sprocket can be divided into four stages: evaluation, pretreatment, reverse engineering, and processing. The specific setups are shown in Fig. 6. A reciprocating path for laser cladding was adopted in the process of sprocket remanufacturing. The overlap rate of the adjacent cladding tracks is 45%, and the lifting amount of each cladding layer along the \( Z \)-axis is 0.4 mm. The experimental equipment and stage are shown in Fig. 7. Figure 7a is the diagram of the laser repair process being carried out. Figure 7b and c show the morphology of the remanufactured sprocket at the halfway stage and at the final stage, respectively.

### 4.2 Microstructure

Characterized in Fig. 8 is the microstructure from the cladding region of the partial repairing sprocket tooth. It is obvious that the microstructure of a cladding layer is composed of heat-affected zone of the substrate, interfacial diffusion zone, and cladding zone. As seen in Fig. 8a, the heat-affected zone and the interfacial diffusion zone have a layer of chilled zone structure, which is a luminous white area formed at the interface junction between the substrate and cladding layer, exhibiting a superb metallurgical bonding between the cladding zone and substrate. Columnar crystal and dendritic crystal along the heat transfer direction can be seen at the cladding zone, as shown in Fig. 8b and c. Li [30] and Liu [31] believe that the change of grain
morphology of metallographic structure is caused by the difference of ratio of temperature gradient to solidification rate (i.e., G/R) at different positions during solidification. In the process of laser cladding, the cladding layer dissipates main heat through the substrate, resulting in the maximum temperature gradient along with the perpendicular interface. G/R at the interface between the substrate and the fusion zone is relatively high, so it is easy to form columnar dendrites.

With the development of solidification process and the accumulation of heat, the temperature gradient decreases gradually, and the cladding region exhibits an increases tendency to dissipate heat to the outside [19, 32]. The cooling rate of the outer surface of the cladding region is accelerated to form dendritic crystals and tends to shift to smaller crystal structure. It can be seen from the metallographic structure of heat-affected zone materials in Fig. 8d that the non-layered structure composed of ferrite and cementite is the performance of austenitization of crystal structure in the heat-affected zone after laser irradiation, and the non-layered structure has a stable strength and toughness coordination. In general, the sprocket cladding area is uniform and dense, the fusion zone and the substrate are well metallurgically bonded, and there are no microcracks and defects generated.

Fig. 6 Remanufacturing experimental setup of damaged sprocket

Fig. 7 Sprocket remanufacturing process and its repair state. a Experimental equipment. b Laser processing. c Halfway stage. d Remanufactured sprocket
4.3 Microhardness

The microhardness of the specimen was measured by selecting 20 measuring points (distance between each measuring point is 0.1 mm, and there are 10 measuring points in the coating zone, which is 1 mm distance from the cladding area to the substrate) evenly along the direction of the cladding area to the cross section of the substrate. Figure 9 shows the change curve of microhardness from the cladding area to the substrate. The microhardness decreases gradually from the cladding area to the heat-affected region and the substrate. It can be seen that the microhardness of the cladding area can reach 550 HV$_{0.5}$~650 HV$_{0.5}$, which is notably superior to the substrate (350 HV$_{0.5}$). The reason for this trend is that there are a lot of alloying elements in the cladding powder, which leads to the enhancement of the solid solution strengthening between the elements inside the cladding layer, resulting in a higher hardness of the cladding layer than the hardness of the substrate [33].

As the measuring point moves toward the fusion zone, the hardness gradually decreases but is higher than the hardness of the substrate. This is due to the dispersion phenomenon of eutectic compounds in the fusion zone, which plays the role of hardness strengthening. Meanwhile, the rapid solidification leads to uniform and dense metallographic structure, resulting in the phenomenon that the hardness of the fusion zone is higher than the base substrate but lower than that of the cladding layer. When the measuring point enters the heat-affected zone, the decreasing trend of hardness slows down [34]. The main reason is that the heat-affected zone is quenched under the action of high temperature, and a small number of alloy elements in the fusion zone diffuse into the heat-affected zone so that the hardness of the heat-affected zone is lower than that of the fusion zone but slightly higher than that of the substrate. When the measuring point leaves the heat-affected zone and enters the substrate, the hardness changes tend to be stable. It demonstrates that the laser cladding technology can significantly improve the microhardness and wear resistance of sprocket tooth in the cladding area of the remanufactured sprocket.
5 Conclusions

(1) The main process parameters affecting the cladding height and the cladding zone area are the scanning speed and the powder feeding rate. Scanning speed $V$ is the main influencing factor of the fusion zone area. The change of dilution ratio is mainly affected by the powder feeding rate. The influence of laser power on the geometric characteristics of cladding is weak.

(2) The predictive relationship model between cladding geometry parameters and laser processing parameters can be expressed as the following formula of $y = k(P^a V^b F^c) + b$. The prediction model of cladding height ($H_c$), cladding zone area ($A_c$), fusion zone area ($A_{mf}$), and dilution ratio ($D$) is established respectively with a correlation coefficient $R^2$ from 0.8663 to 0.9365. All the predicted models show strong correlation and small residual value.

(3) A laser remanufacturing multi-objective optimization problem was constructed with maximizing cladding height ($H_c$), maximizing cladding zone area ($A_c$), minimizing fusion zone area ($A_{mf}$), and minimizing dilution ratio ($D$). The optimization model of multi-objective process parameters for laser remanufacturing of sprocket tooth is solved by MOPSO algorithm. The optimal process parameters of sprocket remanufacturing are laser power $P = 1150$ W, scanning speed $V = 950$ mm/min, and powder feeding rate $F = 3.8$ rad/min.

(4) After repairing, the sprocket tooth cladding area is well metallurgically bonded with the substrate, and there are no microcracks or porosity defects generated. The microhardness decreases gradually from the cladding area to the heat-affected region and the substrate. The microhardness of the cladding area can reach 550 HV$_{0.5}$ ~ 650 HV$_{0.5}$, which is particularly superior to the substrate (350 HV$_{0.5}$).

Author contribution Chenguang Guo: Investigation, resources, writing—original draft.
Ning Lv: Formal analysis, software, investigation, writing—original draft.
Haitao Yue: Conceptualization, methodology, supervision, writing—review and editing.
Qiang Li: Supervision, data curation.
Jianzhuo Zhang: Validation, resources.

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Declarations

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