Research On The Mapping Grinding of Dimple Surface With Ordered Pattern Based On Topological Theory

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Research on the Mapping Grinding of Dimple Surface with Ordered Pattern

Based on Topological Theory

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Abstract

In order to grind structured dimple surface, a topological mapping grinding method for structured dimple surface was proposed based on grinding kinematics principle and point set topology. Firstly, the topological space of the workpiece and the grinding wheel was established, and the topological features of the structured dimple surface and the structured grinding wheel were extracted based on the analysis of the morphology features of the structured surface with array, staggered and phyllotactic pattern. Then, the topology mapping equation of the grinding process was constructed based on the analysis of the generating mechanism of the dimple surface about grinding geometry, and the structured grinding wheel was designed according to the topology mapping equation. Finally, according to the grinding geometry simulation, the influence of grinding parameters on the generating of dimple surface morphology was studied, and the grinding experiment was carried out. The results show that the structured grinding wheel designed according to the topological features of the structured dimple surface can achieve the grinding of the structured dimple surface. The ground dimple surface is a topological dimple surface, and the feature parameters of the dimple surface can be changed with the change of grinding parameters, but the topological feature properties remain unchanged under the condition of satisfying the proper grinding speed ratio.

Keywords: Grinding, Topological grinding, Structured dimple surface, Structured grinding wheel

1 Introduction

“Structured”, “textured” or “engineered” surfaces are important for improving the performance of mechanical parts or products [1]. In recent years, with the continuous development of surface biomimetic technology, the theoretical research on structured surfaces has continued to deepen, and its surface morphology has also tended to be diverse [2, 3, 4]. In particular, the research on bionic structured drag reduction surfaces has attracted more and more attention from scholars and engineers, and has become one of the important research directions in the field of surface engineering design [5, 6, 7, 8]. However, how to put the theoretical research results of structured drag reduction surfaces into practical engineering applications, the research on the high-efficiency or high-precision and low-cost manufacturing technology of the surface has become a bridge between theoretical research results and practical engineering. At present, the manufacturing methods of structured surfaces mainly include rolling method, imprinting method, electrolytic etching method, laser ablation method, photolithography mask method, cutting and grinding, etc. [9-14]. Among them, the grinding method is one of the economical or efficient manufacturing methods to realize the structured surface of difficult-to-machine material parts or the structured surface of mass-produced parts. In the field of structured surface grinding, its research is mainly reflected in the following aspects:

In the research of using spiral grooved grinding wheel to grind structured surface, Stepień Piotr

[15-19] first proposed a method of dressing spiral grooves on the surface of the grinding wheel to grind the surface texture of grooves, convex-hulls and dimples. The corresponding structured surface was cut out, and the creation mechanism of the surface was studied in depth. On this basis, Kim H and Ko T J [20, 21, 22] used the CAM simulation method to design a parametric grinding wheel, and analyzed the influences of the grinding wheel dressing geometric parameters and grinding parameters on the surface morphology of the workpiece. Cao H Y [23] developed the dressing theory of spiral groove grinding wheel and the grinding control strategy of cylindrical structured surface. Liu YM [24] developed the influence law of the dressing spiral groove on the structured surface morphology and grinding force of the workpiece, and established the structured morphology and grinding force model of the workpiece. The model prediction results and the experimental results have good consistency. Mohamed AL-M [25] carried out the research on predicting the surface texture of the workpiece surface with the circumferential groove grinding wheel. Through the study of the influence of grinding parameters, grinding direction and groove coefficients on the structured surface height, spacing and angle on the surface structure, a surface prediction model was established to realize the prediction of structured surface morphology.

In order to realize the grinding of multi-form structured surfaces, Oliveira J F G. and Silva E J [26-29] proposed a dressing method for grinding wheel, and the grinding wheel dressed by this method was used to grind friction reduction surfaces with various structured morphologies such as triangle wave, groove, dimple and convex-hull, also provides the kinematic conditions for realizing structured surface grinding. Moreno M G [30] applied this research to the grinding of the friction reduction surface of the machine tool guide rail, and studied the friction performance of the ground surface to improve the wear resistance of the guide rail, which proved that the application of this grinding technology is feasible.

In the grinding of structured groove drag reduction surface, Denkena B [31-34] carried out the research of groove profile grinding based on the geometric morphology of the shark riblet surface. With the help of the shaping and dressing of the grinding wheel, the surface of the compressor blade realizes the grinding of the riblet surface, and the generating mechanism of the burrs during grinding process and the influence of the grinding wheel wear on the groove geometry are also deeply studied, and corresponding solutions are given. At the same time, a new grinding wheel with a nutria-like tooth structure was proposed. Xie J [35, 36] carried out a research on the grinding of the micro-groove array on the rake face of titanium alloy cutting tools, which improved the cutting performance of the tool. Wu M T and Guo B [37] used lasers to structure the coarse-grained diamond grinding wheel and realized the micro-structure grinding on SiC material surface.

In terms of theoretical research on the design of grinding wheels for structured surface grinding, although in order to improve the grinding performance of the grinding wheel, the research on structured grinding wheels has made good progress [38], However, the theoretical research on the design of structured grinding wheels for grinding complex structured surfaces is relatively weak. Monie A and Guo B [39] conducted research on this problem and gave meaningful design strategies.

The above-mentioned research has promoted the development of structured surface grinding very well. However, it can also be seen that in addition to the profile grinding method that can design the grinding wheel according to the structured surface morphology, in most cases, the grinding wheel is dressed to a certain structured morphology, and then the structured surface morphology of the workpiece is obtained by selecting the grinding parameters appropriately, however, the research on designing a structured grinding wheel based on the morphological features of the structured surface and then grinding the corresponding structured surface is relatively weak, which make the study of the grinding theory of structured surface have a certain degree of passivity and is not conducive to the practical

application of structured surface grinding. Therefore, based on the point set topology theory [40] and the principle of grinding kinematics, this paper proposes a topological mapping grinding strategy for structured dimple surface.

As shown in Fig. 1, suppose the coordinate system of the grinding wheel is $\mathbf{S} (O_s, X_s, Y_s, Z_s)$, the coordinate system of the workpiece is $\mathbf{W} (O_w, X_w, Y_w, Z_w)$, and the center of $\mathbf{S} (O_s, X_s, Y_s, Z_s)$ is at the rotation center of the grinding wheel end face and the center of $\mathbf{W} (O_w, X_w, Y_w, Z_w)$ is at the center of the first dimple being ground. In the grinding process of dimple surface, when the grinding parameters (grinding wheel speed n_s , feed speed v_w and grinding depth a_p) meet the appropriate functional relationship, the abrasive cluster subset S_{ij} on the grinding wheel surface with the base radius R_s can remapped and ground out the dimple subset W_{ij} on workpiece surface in a broad sense. In this process, the abrasives with randomly

Fig. 1 Schematic diagram of the topological mapping of grinding the dimple surface with the structured wheel

wheel, which makes it difficult to obtain accurate grinding dimples in accordance with the design dimple by the replay grinding method. However, from the analysis of theoretical research results of structural friction reduction surface, it can be known that the drag reduction or friction reduction performance of dimple surface is related to the geometric shape of the dimple surface, and more importantly, it is related to some feature parameters of its structure [5-8,41-44], which has topological features. Therefore, based on the topology theory, the structured grinding wheel is designed according to the topological features of the dimple surface of the workpiece, and then the topological surface of the workpiece is mapped to meet the use function of the dimple surface of the ground workpiece. Through this grinding method, not only the grinding process of the dimple surface can be simplified, but also the potential of structured grinding wheels for grinding dimple surfaces can be expanded.

3 Theory of the topological grinding for dimple surface

3.1 Establishment of topological space in grinding process

In the process of dimple grinding as shown in Fig. 1, the Euclidean space of the grinding wheel and the Euclidean space of the workpiece are both measurable spaces, which satisfy the relevant elements of the topological space [40]. Therefore, if the topological space of the grinding wheel is $\mathbf{S}_T$ and the topological space of the workpiece is $\mathbf{W}_T$, the grinding process of the dimple surface can be regarded as the homeomorphic mapping process of the grinding wheel space $\mathbf{S}_T$ to the workpiece space $\mathbf{W}_T$ [40], namely:

$$f: \mathbf{S}_T \rightarrow \mathbf{W}_T \quad (1)$$

Where $\mathbf{S}_T = [\cup S_{ij}, i = 1, 2, 3, \dots, I_s, j = 1, 2, 3, \dots, J_s]$ is represented as the composition of abrasive cluster subset space, I_s and J_s are the maximum ordinals of the abrasive cluster structured units in the axial direction and circumferential direction of the wheel. $\mathbf{W}_T = [\cup W_{ij}, i = 1, 2, 3, \dots, I_w, j = 1, 2, 3, \dots, J_w]$ is represented as the composition of dimple subset space on workpiece surface, I_w and J_w are the maximum ordinals of the rows and columns on the workpiece surface corresponding to the arrangement of the abrasive cluster subset. $f = f(n_s, v_w, a_p, \dots)$ is a topological mapping function determined by grinding parameters and grinding wheel geometric parameters. In the grinding process, S_{ij} with convex set features is mapped to an anticonvex set W_{ij} on the workpiece surface with the $1/n_s$ as the cycle. Of course, this is only an abstract expression in the sense of topology, and the actual grinding process is a

Fig. 2 Schematic diagram of the residual area of dimple grinding

physical process in which the dimple surface is obtained through the removal of material.

3.2 Modeling of the topological features of dimple surfaces

3.2.1 Modeling of the structured dimple surface

From the perspective of morphology, structured friction-reducing surface with dimples has a variety of geometric shapes, and each structured dimple surface is formed by dimple elements with specific shapes arranged on the workpiece surface in accordance with certain rules. The shape, size and arrangement of the dimples affect the surface performance for friction-reducing [41-45]. For example, the shape of the dimple has a spherical crown, an ellipsoidal crown, a rectangle, a triangle, etc., and the arrangement of the dimples can be array, staggered, phyllotactic, and random or arrangement following a specific function. In order to facilitate discussion and analysis of issues, taking the array, staggered and phyllotactic arrangement of spherical crown-shaped dimples as an example, the topological feature modeling and analysis are carried out. Fig. 3 shows the Euclidean space parameter description of the three kinds of dimple arrangement surface. The dimple is a spherical crown.

In Fig. 3a, the mathematical description equation of Euclidean space is given by taking the elliptic dimple structure unit as an example. For the convenience of studying the problem, the contour is deformed topologically into ellipsoid crown or spherical crown shape, and the deformation does not overlap, does not produce sharp points, and does not change convex-concave of the contour. Therefore, taking the center of the dimple as the center of the elliptical dimple unit and keeping it consistent with the workpiece coordinate system, the mathematical model of the dimple is as follows:

$$\begin{cases} \frac{4x_w^2}{l_w^2} + \frac{4y_w^2}{w_w^2} \leq 1 \\ z_w = -\frac{h_w}{c_w} \left[\sqrt{h_w^2 - \frac{4c_w(2h_w-c_w)x_w^2}{(l_w)^2} - \frac{4c_w(2h_w-c_w)y_w^2}{(w_w)^2}} - h_w + c_w \right] \end{cases} \quad (2)$$

Where, c_w is the radius of the z_w axis of the ellipse where the ellipsoid crown is located, and l_w , w_w and h_w are the length, width and depth of the dimple unit respectively. When $l_w > w_w$, the shape of the dimple unit is elliptic crown. When $l_w = w_w$, the shape of the dimple unit is spherical crown.

Fig.3 Schematic diagram of the dimple of workpiece surface and its arrangement

For the three regular dimple arrangements shown in Fig. 2b, Fig. 2c and Fig. 2d, there is a certain arrangement interval and position deviation between adjacent dimple units. Therefore, let the interval between dimple units in the same row or column form the arrangement cycle of the x_w -axis direction and the y_w -axis direction as T_{wx} and T_{wy} respectively. The deviation between the positions of different rows and columns results in the phase differences of ϕ_{wx} and ϕ_{wy} in the two directions. For the array pattern, The arrangement interval of the structural unit is controlled by the arrangement cycle T_{wx} and T_{wy} . The rows and rows are arranged neatly, and the phase difference is $\phi_{wx} = \phi_{wy} = 0$. The cycle of staggered pattern is T_{wx} and T_{wy} , respectively. In the case of equal arrangement, the phase difference between even and odd rows in the staggered pattern is $\phi_{wx} = T_{wx}/2$, and the phase difference between even and odd columns is $\phi_{wy} = T_{wy}/2$. The phyllodes arrangement here is the expansion arrangement of the Iterson G Van model [46] based on the cylindrical arrangement with radius R_b and growth order c , that is, an arrangement on a plane with an expansion length of $2\pi R_b$ [47]. The cycle of expansion is $T_{wx} = T_{wy} = 0$, the phase difference $\phi_{wx} = 2\pi R_b[(i-1)\theta/360 - m + 1]$ in the x_w direction and the phase difference $\phi_{wy} = c(i-1)$ in the y_w direction, and each dimple unit is not in the same row and column. Then Eq (1) can be regarded as the basic dimple, and the mathematical equation of the central position of any dimple can be established. The equation is as follows:

(a) Array pattern:

$$\begin{cases} x_{wo}^{ij} = (j-1)T_{wx} , \\ y_{wo}^{ij} = (i-1)T_{wy}, \\ z_{wo}^{ij} = 0 . \end{cases} \quad (3)$$

(b) Staggered pattern:

$$\begin{cases} x_{wo}^{ij} = \frac{(j-1)T_{wx}}{2}, \\ y_{wo}^{ij} = \frac{(i-1)T_{wy}}{2}, \\ z_{wo}^{ij} = 0 . \end{cases} \quad i, j \text{ are both odd or even.} \quad (4)$$

(c) Phyllotactic pattern:

$$\begin{cases} x_{wo}^{ij} = \phi_{wx} = 2\pi R_b \left[\frac{(j-1)\theta}{360} - m + 1 \right], \\ y_{wo}^{ij} = \phi_{wy} = c(i-1), \\ z_{wo}^{ij} = 0 . \end{cases} \quad (5)$$

In Eqs. (2), (3) and (4), $i = 1, 2, 3, \dots, I_w$. $j = 1, 2, 3, \dots, J_w$, $(x_{wo}^{ij}, y_{wo}^{ij}, z_{wo}^{ij})$ is the coordinate of the center point of the dimple W_{ij} . i is the ordinal number of the row, and j is the ordinal number of the column. For staggered pattern, i and j must be both odd or both even. For the phyllotactic pattern, the phyllotactic angle $\theta = 137.508^\circ$, $i = j = 1, 2, 3, \dots, I_w$, is the ordinal number of structural units. m is the ordinal number that controls the j th structural unit in the x_w -axis direction, and $m \leq (j-1)\theta/360 \leq m+1$, $m = 1, 2, 3, \dots, M$.

3.2.2 Establishment of the topological feature vectors of the dimple surface

According to the topological grinding strategy in Section 1, it is necessary to ensure that the main features of the workpiece surface remain unchanged during the topological grinding process. In order to simplify the problem, for the three kinds of structured dimple surfaces described in equations (2) to (5), only some main parameters are extracted as topological invariants, which are used as topological properties of dimple surfaces. For the point set W_{ij} of the dimple unit, the length l_w , width w_w and depth

h_w of the unit can be used to establish the matrix $\mathbf{W}_d$ that controls the shape and size of the dimple unit and the attributes of the anticonvex set of the dimple. As for the arrangement rule between units, the arrangement cycle (T_{wx}, T_{wy}) and the phase difference (ϕ_{wx}, ϕ_{wy}) can be used as the arrangement attribute between control units and the neighborhood attribute of adjacent dimples. Thus, l_w , w_w and h_w are extracted as the topological feature parameters of the structural unit, and T_{wx} , T_{wy} , ϕ_{wx} and ϕ_{wy} were taken as the arranged topological feature parameters. The topological feature vector and the arranged topological feature vector of dimple units were established. Topological feature vector is as follows:

(1) Topological feature vector of the dimple unit:

$$\mathbf{W}_d = [L_w \quad W_w \quad H_w \quad 1]^T \quad (6)$$

In Eq. (6), L_w , W_w and H_w are the set of feature parameters that describe the length, width and depth of the geometric morphology of the dimple, respectively, and are a set of feature parameters corresponding to the direction of the maximum parameters l_w , w_w , and h_w , which can reflect the using function. In actual operation, the $X_w O_w Y_w$ coordinate plane and the $X_w O_w Z_w$ coordinate plane are equally spaced and discrete to determine these parameters.

(2) Arranged topological feature vector:

Let the topological feature vector of the dimple arrangement be as follows:

$$\mathbf{W}_a = [T_{wx} \quad T_{wy} \quad \phi_{wx} \quad \phi_{wy}]^T \quad (7)$$

Then the feature parameter vectors corresponding to three specific arrangements are as follows:

(a) array pattern:

$$\mathbf{W}_{aa} = [T_{wx} \quad T_{wy} \quad 0 \quad 0]^T \quad (8)$$

(b) Staggered pattern:

$$\mathbf{W}_{as} = \left[T_{wx} \quad T_{wy} \quad \frac{T_{wx}}{2} \quad \frac{T_{wy}}{2} \right]^T \quad (9)$$

(c) phyllotactic pattern:

$$\mathbf{W}_{ap} = \left[0 \quad 0 \quad 2\pi R_b \left[\frac{(j-1)\theta}{360} - m + 1 \right] \quad c(j-1) \right]^T \quad (10)$$

3.3 Topology analysis and modeling of structured grinding wheel

3.3.1 Modeling of the structured surface of grinding wheel

Fig.3 is the morphology of the structured grinding wheel corresponding to the arrangement of three kinds of abrasive clusters adopted in Fig. 1. In the process of topological mapping grinding, the circumscribed geometric properties and layout properties of the abrasive cluster S_{ij} on the wheel surface will be topologically mapped along the X_w -axis of the workpiece coordinate system according to the different grinding parameters. Its radial topological properties will be mapped along the Z_w axis of the workpiece according to the different grinding parameters, while the axial properties will remain unchanged and map to the Y_w axis direction of the workpiece. For the convenience of discussion, the circumferential arc length, axial width and radial height of the abrasive cluster of the structured grinding wheel are set as l_s , w_s and h_s respectively corresponding to l_w , w_w and h_w of the dimple unit. Then the point set of the abrasive cluster S_{ij} will be obtained from the point set of the dimple W_{ij} on the workpiece surface through topological mapping. Therefore, the equation of abrasive cluster unit on the grinding wheel surface is described as:

$$f_s(x_s, y_s, z_s) = 0, \quad (x_s, y_s, z_s) \in S_{ij} \quad (11)$$

Suppose that the arc length arrangement cycle T_{sl} and axial cycle T_{sy} of the abrasive clusters in the grinding wheel with the circle radius R_s of the substrate correspond to the arrangement cycle T_{wx} and

T_{wy} of the dimples on the workpiece surface respectively; The arc length phase difference ϕ_{sl} and axial phase difference ϕ_{sy} of the abrasive clusters correspond to the ϕ_{wx} and ϕ_{wy} of the dimples on the workpiece surface, respectively; then, for the array pattern of abrasive clusters shown in Fig. 4a, there will be $\phi_{sl} = 0$ and $\phi_{sy} = 0$; for the staggered pattern shown in Fig. 4b, there are $\phi_{sl} = T_{sl}/2$ and $\phi_{sy} = T_{sy}/2$; for the phyllotactic pattern shown in Fig. 4c, each circle on the circumference of the grinding wheel and each axial generatrix have only one abrasive cluster unit, and the position of the abrasive cluster on the circumference of the grinding wheel can be described by the phase difference between each other, therefore, according to the Iterson G Van model [46] of the phyllotactic pattern on cylinder surface, $\phi_{sl} = (j - 1)R_s\theta\pi/180$ and $\phi_{sy} = c(i - 1)$. Therefore, the position equation of the abrasive cluster is expressed as follows:

(a) Array pattern:

$$\begin{cases} x_{so}^{ij} = R_s \cos \left[\frac{(j-1)T_{sx}}{R_s} \right], \\ y_{so}^{ij} = (i - 1)T_{sy}, \\ z_{so}^{ij} = R_s \sin \left[\frac{(j-1)T_{sx}}{R_s} \right]. \end{cases} \quad (12)$$

(b) Staggered pattern:

Fig.4 Schematic diagram of structured grinding wheel

$$\begin{cases} x_{so}^{ij} = R_s \cos \left[\frac{(j-1)T_{sx}}{2R_s} \right], \\ y_{so}^{ij} = \frac{(i-1)T_{sy}}{2}, \\ z_{so}^{ij} = R_s \sin \left[\frac{(j-1)T_{sx}}{2R_s} \right]. \end{cases} \quad (13)$$

(c) Phyllotactic pattern:

$$\begin{cases} x_{so}^{ij} = R_s \cos \left(\frac{\phi_{sl}}{R_s} \right) = R_s \cos \left[\frac{(j-1)\theta\pi}{180} \right], \\ y_{so}^{ij} = \phi_{sy} = c(i-1), \\ z_{so}^{ij} = R_s \sin \left(\frac{\phi_{sl}}{R_s} \right) = R_s \sin \left[\frac{\theta(j-1)\pi}{180} \right]. \end{cases} \quad (14)$$

In Eqs. (12) to (14), $i = 1, 2, \dots, I_s$, $j = 1, 2, \dots, J_s$. I_s is the axial ranking number of abrasive clusters on the

wheel surface; J_s is the number of circumferential rows of abrasive clusters. For staggered pattern, i and j must be odd or even, at the same time. For phyllotactic pattern, $i = j = 1, 2, \dots, I_s, I_s = J_s$. $(x_{so}^{ij}, y_{so}^{ij}, z_{so}^{ij})$ is the position coordinates of the center of the abrasive cluster.

3.3.2 Establishment of the topological feature vectors of grinding wheel

During the grinding process, the topological features of the grinding wheel surface are correspondingly mapped to the workpiece surface. Based on the above analysis of the abrasive clusters of the grinding wheel and the established equations, the geometric and arrangement topological parameters of the abrasive clusters can be extracted, and the topological feature vector $\mathbf{S}_d$ of the abrasive clusters on the wheel surface and the topological feature vector $\mathbf{S}_a$ of its arrangement can be established, as follows:

(1) Topological feature vector of abrasive cluster unit

$$\mathbf{S}_d = [L_s \quad W_s \quad H_s \quad 1]^T \quad (15)$$

In Eq. (15), L_s is the set of feature arc lengths of the abrasive clusters along the cylindrical surface of the wheel substrate. W_s is the set of the feature widths of the abrasive clusters along the axial direction of the cylindrical surface, and H_s is the set of the feature heights of the abrasive clusters relative to the normal direction of the cylindrical surface. L_s , W_s and H_s correspond to L_w , W_w and H_w of the dimple unit on the workpiece surface.

(2) Topological feature vector of the arrangement of abrasive clusters

Suppose the feature vector of the arrangement of abrasive clusters is:

$$\mathbf{S}_a = [T_{sl} \quad T_{sy} \quad \phi_{sl} \quad \phi_{sy}]^T \quad (16)$$

Then, the topological feature vectors of the three abrasive clusters corresponding to Eq. (16) are as follows:

(a) Array pattern:

$$\mathbf{S}_{aa} = [T_{sl} \quad T_{sy} \quad 0 \quad 0]^T \quad (17)$$

(b) Staggered pattern:

$$\mathbf{S}_{as} = \left[T_{sl} \quad T_{sy} \quad \frac{T_{sl}}{2} \quad \frac{T_{sy}}{2} \right]^T \quad (18)$$

(c) Phyllotactic pattern:

$$\mathbf{S}_{ap} = \left[T_{sl} \quad T_{sy} \quad \frac{(j-1)R_s\theta\pi}{180} \quad c(i-1) \right]^T \quad (19)$$

3.4 Topological mapping matrix of grinding dimple process

(1) Analysis of the mapping process of generating dimple surface

In the process of grinding the surface of the dimple, the structured grinding wheel grinds the surface of the workpiece by an up-grinding method. The abrasive particles of the abrasive cluster make an extended epicycloid motion relative to the workpiece, and the cutting sequence of each abrasive grain in the circumferential direction of the grinding wheel is different, and its radial protrusion height is also different, so it produces overlapping trajectories in the cross-section that interferes with the workpiece, removes material through the envelope [48], and generates a dimple geometry. Fig. 5 shows the motion trajectory diagram of the enveloping dimples in the X_w direction of a plurality of abrasive grains on two adjacent abrasive clusters. It is not difficult to know from Fig. 1 that in the process of mapping dimples from the abrasive cluster topology, no relative movement occurs between the Y_s direction of the grinding wheel and the Y_w direction of the workpiece. Therefore, the geometric mapping between the topology feature width W_s of the abrasive cluster and the topology feature width W_w of the dimple maintain an

workpiece, and the B_s point is cut out from the B_w point of the workpiece, and a dimple unit $\overline{A_w B_w}$ ($= l_w$) is ground. The $\overline{B_s C_s}$ section of the grinding wheel surface has no abrasive contact with the workpiece, and forms the $\overline{B_w C_w}$ section corresponding to the workpiece surface, which becomes the platform-shaped separation interval between the dimple units, and the interval length is l_{wBC} . When $l_{wBC} \geq 0$, a dimpled surface is grinded on the workpiece surface. In fact, it can be inferred from Fig. 6 that adjacent dimple elements intersect when $T_{wx} < l_w$; the dimple units are connected when $T_{wx} = l_w$; the dimple units are separated and a dimple-type structured surface can be generated when $T_{wx} > l_w$. Therefore, based on the grinding kinematics relationship, when the abrasive clusters of the grinding wheel rotate for one cycle time, that is, $\mathcal{P}_s/2\pi n_s = T_{sl}/2\pi n_s R_s$, the workpiece will be fed with v_w for an arrangement cycle T_{wx} , the relationship between the arrangement cycles T_{sl} and T_{wx} is as follows:

$$T_{wx} = \frac{\mathcal{P}_s}{2\pi n_s} \times v_w = \frac{T_{sl}}{2\pi R_s} \times \frac{v_w}{n_s} \quad (20)$$

In Eq. (20), $\mathcal{P}_s = 2\pi/N$ is the center angle of adjacent abrasive clusters, and N is the largest ordinal number of abrasive clusters arranged on the same circumference of the grinding wheel. For array and staggered pattern, $N = J_s$; for phyllotactic pattern, $N = 1$.

Similarly, since the geometric position relationship between the arrangement cycle T_{sl} and the phase difference ϕ_{ls} is fixed, the following relationship also exists between the phase difference ϕ_{ls} and ϕ_{wx} :

$$\phi_{wx} = \frac{\mathcal{P}_s}{2\pi n_s} \times v_w = \frac{\phi_{sl}}{2\pi R_s} \times \frac{v_w}{n_s} \quad (21)$$

In the actual design of the radial geometry of the abrasive cluster on the surface of the grinding wheel base, it is necessary to ensure that the radial height growth rate of the inlet section and the attenuation rate of the cutting section of the abrasive cluster as shown in Fig. 6 can enable continuous progressive grinding when grinding the dimples on the workpiece surface, without rapidly increasing the grinding depth. In this process, the generating length l_w of the dimple in the X_w direction is the combined effect of the geometric interference chord length of the grinding wheel under the condition of the grinding depth a_p of the abrasive cluster and the movement length of the workpiece during the cutting-in and cutting-out time of the abrasive cluster[49]. However, due to the different radii of the abrasives on the abrasive clusters relative to the center of the grinding wheel, the chord length of the interference changes, and the chord length increases with the change of feed time is also non-linear. Therefore, it can be approximately simplified as the generating length of the dimple is composed of the interference chord length at the average grinding depth $\overline{a_p}$ and the average feed motion length in the X_w direction when the grinding wheel rotates through the abrasive cluster area, namely:

$$l_w \approx \frac{l_s}{2\pi R_s} \times \frac{v_w}{n_s} + 2\sqrt{2\overline{R_s}\overline{a_p}} \quad (22)$$

In Eq.(22), $\overline{R_s}$ is the average value of the radial radius of the abrasive clusters corresponding to the l_s section. $\overline{a_p}$ is the average value of the abrasive cluster radius. In the grinding mapping process, from the perspective of the grinding depth identity mapping, $a_p = h_s = h_w$ can be determined. Under the condition that the feature parameter of the depth of the dimple is directly mapped along the radial direction of the grinding wheel, the values of $\overline{R_s}$ and $\overline{a_p}$ can be calculated.

(2) Topological mapping matrix between workpiece and grinding wheel

According to the above analysis of the generating process of the maximum feature size and arrangement of the dimples, it can be seen that the topological corresponding relationship between the dimple and the abrasive cluster is equivalent transformation in the width and depth directions, while the topological deformation of stretching and bending occurs in the length direction due to the influences of

the contour shape of the abrasive cluster and grinding parameters. Moreover, there is one - to - one mapping relationship between the set points of the dimple and the set points of the abrasive cluster as well as the arrangement relation, which forms a topological mapping relationship. Therefore, according to equations (20), (21) and (22) and the analysis results of the mapping relationship of the dimples in different directions, the size topological mapping matrix $\mathbf{F}_d$ and the arrangement topological mapping matrix $\mathbf{F}_a$ in the grinding process can be established as follows:

(a) Topological mapping matrix of the size features:

$$\mathbf{F}_d = \begin{bmatrix} \frac{v_w}{2\pi R_s n_s} & 0 & 0 & 2\sqrt{2\bar{R}_s^s \bar{a}_p^s} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (23)$$

Where $\bar{R}_s^s$ is the average radius in the area corresponding to the length of the s -th divided section of the abrasive cluster, $\bar{a}_p^s$ is the average grinding depth of the s -th divided section. When the abrasive cluster is the maximum length l_s , $\bar{R}_s^s = \bar{R}_s$ and $\bar{a}_p^s = \bar{a}_p$.

(b) Topological mapping matrix of the arrangement features:

$$\mathbf{F}_a = \begin{bmatrix} \frac{v_w}{2\pi R_s n_s} & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{v_w}{2\pi R_s n_s} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (24)$$

Therefore, based on equations (6), (7), (15), (16) and (23), (24), the topological mapping equations in the grinding process can be obtained as follows:

$$\begin{cases} \mathbf{W}_d = \mathbf{F}_d \mathbf{S}_d \\ \mathbf{W}_a = \mathbf{F}_a \mathbf{S}_a \end{cases} \quad (25)$$

Similarly, if the mapping of the grinding process is regarded as an identity mapping, for the convenience of designing the grinding wheel, the corresponding inverse mapping relationship from the workpiece to the grinding wheel can be given:

$$\begin{cases} \mathbf{S}_d = \mathbf{F}_d^{-1} \mathbf{W}_d \\ \mathbf{S}_a = \mathbf{F}_a^{-1} \mathbf{W}_a \end{cases} \quad (26)$$

Among them, $\mathbf{F}_d^{-1}$ and $\mathbf{F}_a^{-1}$ are as follows:

$$\mathbf{F}_d^{-1} = \begin{bmatrix} \frac{2\pi R_s n_s}{v_w} & 0 & 0 & -\frac{4\pi R_s n_s}{v_w} \sqrt{2\bar{R}_s^s \bar{a}_p^s} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (27)$$

$$\mathbf{F}_a^{-1} = \begin{bmatrix} \frac{2\pi R_s n_s}{v_w} & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{2\pi R_s n_s}{v_w} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (28)$$

4 Design and manufacturing of structured grinding wheel

4.1 Design of the grinding wheel

In the actual design of the grinding wheel, the substrate radius R_s and the configuration form of the grinding wheel can be given first, as well as the number of circumscribed columns J_s , so that the circumscribed T_{sl} and ϕ_{sl} of the grinding wheel can also be determined first. Then, according to T_{wx} , ϕ_{wx} , T_{wy} and ϕ_{wy} known to the workpiece,

T_{sy} , ϕ_{sy} and v_w/n_s can be determined by using the configuration equations in Eqs. (25) and (26). Then,

according to the feature quantities L_w , W_w and H_w of the dimples, L_s , W_s and H_s are obtained by using the size equations of the dimples in Eqs. (25) and (26).

In the design of the abrasive cluster of the grinding wheel, firstly, the dimple unit shown in Fig. 2a is discretely divided along the equal spacing of X_w and Y_w directions to determine the feature parameter set of length, and at the same time, the depth feature set of Z_w direction is determined. Then, the cylinder surface of the grinding wheel is correspondingly divided in the topological space of the grinding wheel. When the abrasive cluster unit is divided, the axial discrete segmentation corresponds to the Y_w direction division of the workpiece dimple, the circumferential segmentation with discrete equal angle corresponds to the X_w direction division of the workpiece dimple, and then the peripheral size set L_s , axial size set W_s , and the radial size set H_s can be obtained. Finally, the feature dimensions of L_s , W_s and H_s are calculated by using the size mapping equation of abrasive cluster in Eq. (26).

According to the above method, under the condition of the known dimple size as shown in Tab. 1, the arrangement and size parameters of the corresponding abrasive clusters are designed, and the digital

Fig.7 Digital grinding wheel with different arrangement of abrasive clusters

grinding wheels with the array, staggered and phyllotactic pattern of the abrasive clusters shown in Fig. 7 are designed by using software.

Tab. 1. Topological design parameters of workpiece and grinding wheel

Parameters	Workerpiece (known)			Wheel: Diameter $\Phi 60\text{mm}$, Thickness 15mm.		
	Array pattern	Staggered pattern	Phyllotactic pattern	Array pattern	Staggered pattern	Phyllotactic pattern
Unit sizes, mm	$l_w=3$ $w_w=2$ $h_w=0.020$	$l_w=3$ $w_w=2$ $h_w=0.020$	$l_w=3$ $w_w=2$ $h_w=0.020$	$l_s=26$ $w_s=2$ $h_s=0.020$	$l_s=26$ $w_s=2$ $h_s=0.020$	$l_s=26$ $w_s=2$ $h_s=0.020$
Unit arrangement	$T_{wx}=3.25$ $T_{wy}=3$	$T_{wx}=6.5$ $T_{wy}=3$	$T_{wx}=0$ $T_{wy}=0$	$T_{sl}=47.1$ $T_{sy}=3$	$T_{sl}=94.2$ $T_{sy}=3$	$T_{sl}=0$ $T_{sy}=0$
mm $v_w/n_s = 13, a_p = 20\mu\text{m}$	$\phi_{wx}=0$ $\phi_{wy}=0$	$\phi_{wx}=3.25$ $\phi_{wy}=1.5$	$\phi_{wx}=2\pi R_p \left[\frac{(j-1)\theta}{360} - m + 1 \right]$ $\phi_{wy}=0.7 (i-1)$	$\phi_{sl}=0$ $\phi_{sy}=0$	$\phi_{sl}=47.1$ $\phi_{sy}=1.5$	$\phi_{sl}=71.96(j-1)$ $\phi_{sy}=0.7 (i-1)$
Rows and columns	$I_w=5$ $j=1,2,3,\dots,J_w$	$I_w=9$ $j=1,2,3,\dots,J_w$	$I_w=J_w=18$	$I_s=5$ $J_s=4$	$I_s=9$ $J_s=4$	$i=j=1,2,3,\dots,18.$

4.2 Manufacture of the grinding wheel

In the manufacturing process of the grinding wheel, a combination of masking, corrosion and electroplating is used [50, 51], and the process flow is shown in Fig. 8. Firstly, the mask is designed and manufactured according to the structure of the grinding wheel shown in Fig. 7 and the parameters in Tab. 1. Then lithography and corrosion were carried out on the substrate of the grinding wheel to form a

convex hull arranged in order on the substrate surface of the grinding wheel, and the convex hull was precisely shaped to achieve the designed geometric shape. When dressing the geometry of the convex hull, the amount of pre-dressing should be given based on the average diameter of the abrasive size. Finally, the consolidating abrasive grains and thickening coating on the convex hull by electroplating form a grinding wheel to ensure that the contour height of the abrasive clusters meets the design requirements. In order to improve the mechanical properties of the electroplated layer, the electroplated grinding wheel was placed in a thermostat for hydrogen evolution and stress relief. The substrate diameter of the electroplated grinding wheel is $\Phi 60\text{mm}$, and the axial thickness is 15mm. The abrasive used is CBN abrasive with 140/150 mesh. The electroplating solution is a bright nickel plating solution with NiSO_2 as the main salt [50, 51]. Fig. 9 shows an electroplated grinding wheel with an array, staggered and phyllotactic pattern of the abrasive clusters.

Fig . 8 Process flow chart of electroplating grinding wheel

Fig9. Electroplated CBN grinding wheel with ordered abrasive clusters

5 Geometric simulation of grinding dimple surface

5.1 Simulation strategy and conditions

According to the topological feature parameters of Tab. 1 and the digital grinding wheel shown in Fig. 7, the geometric simulation of generating the dimple surface during the grinding process was carried out

using computer software programming. The simulation flow chart is shown in Fig.10. In the simulation, the distance between the grinding wheel and the workpiece surface as shown in Fig. 1 is set as $e = R_s + h_s - a_p$. In the simulation, the position of the abrasive grain relative to the trajectory point of the workpiece surface is calculated according to the trajectory equation of the surface grinding [48], and then the grinding interference state between the abrasive particle and the workpiece is judged to determine the surface topography of the workpiece. CBN abrasive size is 140/150 Mesh, and its average diameter is set to 90 μ m. Only the macroscopic contour of the dimple is considered and the microscopic roughness effect is ignored.

Fig. 10 Simulation flow chart for grinding dimple surface

5.2 Simulation results and analysis

Fig. 11 is the dimple surface with array, staggered and phyllotactic pattern realized by simulation under the designed parameters of Tab.1. And at this time, the dimples of array, staggered and phyllotactic pattern all form a structure in a separated state. The average cycle of the array pattern in the X_w direction is 3.25mm, and the average cycle in the Y_w direction is 3mm. The average cycle of the staggered pattern in the X_w direction is 6.5mm, and the average phase difference is 3.25mm; the average cycle in the Y_w direction is 3mm, and the phase difference is 1.5mm. The initial phase difference in the X_w direction of the phyllotactic pattern is 4.96mm, and the initial average phase difference in the Y_w direction is 0.7mm. The maximum length, width and depth of the dimples are also consistent with the design dimensions. It shows that the topological grinding method can realize the diversification of dimple surface.

In order to obtain the mapping effect of v_w/n_s on the dimple of the workpiece surface, on the basis of the structured grinding wheel designed based on $v_w/n_s = 13$ in Tab. 1, the structured surface morphology of dimples arranged in array was simulated under the conditions of $v_w/n_s = 9, 12, 14$ and 15 respectively, as shown in Fig.12. When $v_w/n_s = 9$, adjacent dimple units intersect in the X_w direction. When $v_w/n_s = 12, 14$ and 15 , with the increase of v_w/n_s , the maximum length of dimple unit in the X_w direction is 2.9mm, 3.09mm and 3.20 mm, respectively, showing an increasing trend, while the width in the Y_w direction remains the same as the design width of 2mm, and the maximum depth remains 20 μm ; Similarly, the arrangement cycle in the X_w direction is 3 mm, 3.5 mm, and 3.75 mm respectively, showing an increasing trend, and the cycle in the Y_w direction also remains unchanged at the design cycle of 3 mm. The simulation results verify the consequences in the design analysis that as the speed ratio further increases, the depth and width of the dimple unit remain unchanged, and the length and cycle of the structural unit increase.

Fig.12 The influence of speed ratios v_w/n_s on the morphology of dimple surface at $a_p = 20\ \mu\text{m}$.

Fig. 11 Simulation diagrams of surface dimple surface with different arrangements at $a_p=20\mu\text{m}$, $n_s=1800\text{r/min}$, $v_w=23400\text{mm/min}$ and $v_w/n_s=13$.

Fig. 13 is the dimple surface morphology obtained based on the simulation conditions of Fig. 11a when the grinding depth is reduced to $10\mu\text{m}$ and $15\mu\text{m}$, respectively. When the grinding depth is $10\mu\text{m}$, $15\mu\text{m}$ and $20\mu\text{m}$, the maximum feature length of the dimple unit is 2.25mm , 2.77mm and 2.9mm , and the width is 1.3mm , 1.7mm and 2mm , respectively. The arrangement cycle in the X_w direction is 3.22mm , and the cycle in the Y_w direction remains unchanged at 3mm .

Fig.13 The influence of grinding depth a_p on the morphology of dimple surface at $v_w/n_s=13$, $n_s=1800\text{r/min}$ and $v_w=23400\text{mm/min}$.

The above Figs. 11, 12 and 13 are just a few examples to illustrate the problem. In fact, we have simulated different grinding parameters in the process of designing the grinding wheel. The results show that with the increase of the grinding depth, the dimple arrangement cycle does not change, the length and width of the dimple unit increase, and the growth rate is gradually reduced by the influence of the dimple shape; When the parameters of the grinding wheel are constant, the speed ratio v_w/n_s not only affects the length and arrangement period of the dimple units in the X_w direction, but also controls the separation, touch

and intersection between the dimple units, thus changing the morphology of structured dimple surface.

6 Grinding experiment

6.1 Experimental setup

The grinding experiment was done on the CNC machining center as shown in Fig. 14. The grinding wheel used is shown in Fig. 9, and the structural parameters of the grinding wheel are shown in Tab. 1. The size of the workpiece is 50mm×25mm×15mm, the workpiece material is 45 steel, its hardness is HRC36-42, and the initial surface roughness is Ra0.3. The workpiece is fixed on the worktable by a precision vise, and grinding method is up-grinding. No coolant is used during grinding, and the Taylor Hobson Form Talysurf *i* profiler is used to measure the three-dimensional topography of the ground surface of the workpiece.

Fig. 14 Experimental setup

6.2 Experimental results and analysis

Fig.15 shows the workpiece surface ground by the grinding wheel with array pattern. The average length of the dimple unit is 3.1mm, the average width is 1.6mm, and the average maximum depth is about 12 μ m. The average arrangement cycle in feed speed direction is 3.2mm, and the cycle in vertical feed speed direction is 3mm. It can be seen that the arrangement parameters of the ground surface are basically the same as the design parameters, but the feature size of the structured unit has a big difference. Through the microscopic observation and measurement of the ground dimples and the analysis of the grinding process, it is found that the reason for this phenomenon is caused by the abrasive distribution features on the surface of the electroplated CBN grinding wheel. When designing and manufacturing the geometric sizes of the abrasive clusters, the average geometric size of the abrasive grains was taken as a reference, and the protruding height of abrasive grains is assumed to be equal, while the actual protruding height of abrasive grains on the surface of the electroplated grinding wheel obeys a normal distribution [52, 53]. When the theoretical grinding depth $a_p=20\mu\text{m}$ is set based on the spark generated by the grinding wheel, only part of the abrasive particles actually participates in the grinding, so that the surface of the dimple is enveloped by rough grooves, and the actual grinding depth does not reach theoretical grinding depth. Therefore, it also shows that improving the protruding height of abrasive grains of the electroplated grinding wheel is very important to realize this grinding method.

(a) Surface image

(b) Three-dimensional surface topography

(c) Mid-section profile

Fig. 15 The surface morphology of the ground workpiece with an array pattern at $a_p=20\mu\text{m}$, $n_s=1800\text{r/min}$, $v_w=23400\text{mm/min}$ and $v_w/n_s=13$.

(a) Surface image

(b) Three-dimensional surface topography

(c) Mid-section profile

Fig. 16 The surface morphology of the ground workpiece with a staggered pattern at $a_p=10\mu\text{m}$, $n_s=1800\text{r/min}$, $v_w=18000\text{mm/min}$ and $v_w/n_s=10$.

Fig.16 shows the ground dimple surface with staggered pattern when the speed ratio is reduced to $v_w/n_s = 10$ and the grinding depth is reduced to $a_p=10\mu\text{m}$ based on the design parameters. The average length of the dimple unit is 2.2mm, the average width is 1.6mm, and the average depth is 8 μm . The average cycle in the feed speed direction is 5 mm, the average cycle in the direction perpendicular to the feed speed is 3 mm, the phase difference in the feed speed direction is 2.5 mm, and the phase difference in the direction perpendicular to the feed speed is 1.5mm. By measuring and observing the dimple structure

of the workpiece surface, it can be known that the topological feature attributes of the dimple surface have not changed, but the topological feature parameters will decrease accordingly. As the grinding depth decreases, the number of abrasive grains involved in the grinding decreases, and the dimpled surface is composed of only a few grinding groove marks of abrasive grains.

Fig. 17 The surface morphology of the ground workpiece with an phyllotactic pattern at $a_p=20\mu\text{m}$, $n_s=1800\text{r/min}$, $v_w=18000\text{mm/min}$ and $v_w/n_s=10$.

Fig. 17 shows the ground dimple surface with the phyllotactic pattern when the speed ratio is reduced to $v_w/n_s = 10$ and the grinding depth is reduced to $a_p=20\mu\text{m}$. The measurement results show that the average length of the dimple unit is 2.7mm, the average width is 1.6mm, the average maximum depth of the dimple is $15\mu\text{m}$, the initial phase difference in the direction of the feed speed is 3.8mm, and the initial phase difference in the direction of the perpendicular to the feed speed is 0.7mm. It can also be seen that the topological properties of the dimple surface remain unchanged. However, it can be seen from mapping equation (25) that intersection of dimples should occur on the ground surface by the grinding wheel designed according to Tab. 1 when the speed ratio decreases from $v_w/n_s = 13$ to $v_w/n_s = 10$, but it does not occur in the actual results. The reason is still the normal distribution of the actual protruding height of abrasive grains on the surface of grinding wheel, and the aligning reference of the grinding depth is based on the highest abrasive point, which results in the actual grinding depth being less than $20\mu\text{m}$ of the theoretical grinding depth.

(a) Surface image

(b) Three-dimensional surface topography

(c) Mid-section profile

Fig. 18 The surface morphology of the ground workpiece with an array pattern at $a_p=20\mu\text{m}$, $n_s=1800\text{r/min}$, $v_w=10800\text{mm/min}$ and $v_w/n_s=6$.

(a) Surface image

(b) Three-dimensional surface topography

(c) Mid-section profile

Fig. 19 The surface morphology of the ground workpiece with an phyllotactic pattern at $a_p=20\mu\text{m}$, $n_s=1800\text{r/min}$, $v_w=10800\text{mm/min}$ and $v_w/n_s=6$.

Fig. 18 and Fig. 19 respectively show the surface morphology of the workpiece ground by the grinding wheel with array pattern and phyllotactic pattern when the speed ratio is reduced from $v_w/n_s = 13$ to $v_w/n_s = 6$. At this time, the dimple surface ground by the grinding wheels with array pattern has already produced an intersecting shape along the feed speed direction, and the corresponding arrangement properties have basically disappeared; the dimple surface ground by the grinding wheel with phyllotactic pattern has produced intersections between the dimples in the vertical direction of the feed speed, but certain topological properties of the arrangement can still be observed. These also indicate that the selection of grinding parameters at this time cannot satisfy the kinematic conditions of generating the dimple surface expressed by Eqs. (20) and (21). However, it can be seen that due to the reduction of the

feed speed of the workpiece, the dynamic grinding edge participating in the grinding of the dimples increases [48, 53], and the cutting groove marks on the surface of the dimples become dense. The actual depth of the dimple increases and the bottom surface becomes smoother, as shown in Fig. 19.

7 Conclusions and Outlook

Based on the geometric topology theory, the mapping relationship matrix between the topological space of workpiece and the topological space of the grinding wheel is established. The structured grinding wheels with abrasive clusters are designed and the analysis and geometric simulation of the surface creation in the topological grinding process are performed. At the same time, the grinding wheel was manufactured and the grinding experiment was carried out. The results show that the topological grinding of the structured dimple surface can be realized by the designed grinding wheel with ordered abrasive clusters based on the topological properties of the dimple surface. Although the ground dimple structured surface is an approximation of the theoretical surface, it still maintains the topological properties unchanged. To achieve the grinding of the structured dimple surface, the selection of grinding parameters must meet the corresponding kinematics conditions. These studies provide a new way for the grinding of the structured surface.

In the follow-up work, the manufacturing quality of grinding wheel should be further improved, such as improving the manufacturing accuracy of the substrate and improving the contour of the protruding height of abrasive grains on the surface of the grinding wheel; the feasibility study of topological grinding for different structured surfaces will also be carried out. The grinding wheel is designed more closely based on the functional feature parameters of the structured surface, and this grinding method is realized, and the precision relationship between the ground topological surface and the designed workpiece surface will be explored in depth.

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Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Guoxun Wang, Xingshan Li and Yongchao Qi. The first draft of the manuscript was written by Yushan Lyu and all authors commented on previous versions of the manuscript. All authors read and approved the

final manuscript.

Availability of data and material

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability

Not applicable

Ethics approval

Written informed consent for publication of this paper was obtained from the Shenyang Ligong University and all authors.

Consent to participate

Not applicable

Consent for publication

The Author confirms: that the work described has not been published before ; that it is not under consideration for publication elsewhere; that its publication has been approved by all co-authors; that its publication has been approved by the responsible authorities at the institution where the work is carried out.

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