A real-time dressing method for metal lapping pads based on the thermal deformation effect

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Abstract
Surface shape and accuracy of the metal lapping pad have a significant impact on the performance of the lapping process for flat optical components, which are usually improved by the dressing process. A real-time dressing system for metal lapping pad surface shape (RDLS system) based on the bimetal thermal deformation effect is proposed. Unlike traditional dressing methods (e.g., turning dressing with a diamond tool), the real-time dressing based on the RDLS system is a material-loss-free and in-process dressing method. A full-aperture lapping turntable based on the RDLS system was designed, in which the working heat was analyzed. The displacement models of the lapping pad surface were established by regression analysis. Finally, several experiments were conducted to verify the functionality of the RDLS system. During turning dressing (turn-table rotational speed \( n = 100 \) rpm), the displacement error was compensated by the RDLS system, which was caused by the working heat of the turntable shaft system. During the lapping processing for optical elements (\( n \leq 20 \) rpm), the correction displacement was controlled by the RDLS system, which realized the real-time dressing of the lapping pad surface. The process performance of the plane optical component was optimized with the RDLS system (process parameter: the coolant temperature \( t \)). The effectiveness and practicality of the RDLS system were demonstrated experimentally.

Keywords Real-time dressing · Bimetal thermal deformation effect · Thermal deformation error compensation · Process parameter optimization

1 Introduction
Plane lapping is used to produce high-precision plane components required for integrated circuits, giant lasers, optical lenses, and other devices [1, 2]. According to recent research, the evaluation criteria for lapping and polishing plane components (including material removal rate, surface roughness, and flatness) are affected by the dressing of the lapping-and-polishing-pad surface [3, 4]. Unless the lapping-and-polishing pad is continually dressed, it experiences glazing, passivation, and wear, and this has a negative impact on the process performance of the plane component [5]. Therefore, improving this dressing process would subsequently improve the process performance of plane components [6, 7].

The use of a diamond dresser is the most traditional practice for dressing a lapping pad [8–11]. However, this method results in material losses, thereby reducing the pad’s service life. To avoid loss of production efficiency due to numerous pad replacements, three categories of more efficient dressing methods have been studied in recent years. First, in-process dressing methods without a diamond dresser have been considered [12]. For example, Chiu et al. [13] proposed a dressing method for a fixed-abrasive lapping pad based on surface coating technology, and this method helped improve the surface roughness of the plane components. Second, dressing methods based on new types of the diamond dresser have been researched [14]. For example, an organic-composite diamond dresser was adopted by Tsai et al. to reduce the material loss of the polishing pad [15]. Finally, the self-dressing effect of lapping and polishing processes has been studied. For example, Lee et al. pointed out...
that self-dressing can be realized in a fixed-abrasive lapping pad by optimizing the process parameters [16]. In summary, with a diamond dresser, material losses of the lapping-and-polishing pad cannot be avoided. Therefore, for efficiency, it is necessary to propose real-time, material-loss-free, and in-process dressing methods.

The tin lapping pads are commonly used in processing optical components such as YAG crystals [17]. Such pads are usually dressed by turning with a diamond tool at a constant speed feed. During the lapping processing, the surface of the pad must be repeatedly corrected to improve process performance. However, turning dressing affects the service life of the pad and the production efficiency of the components. Instead, in this study, a system for the real-time dressing of lapping pad surface shape (RDLS system) is proposed, based on the bimetal thermal deformation effect. This method helps reduce the lapping pad material loss; it is an in-process and real-time dressing method that controls the metal lapping pad surface shape through the correction displacement which is controlled by the RDLS system. Furthermore, this method can effectively improve the service life of tin lapping pads (and therefore component-production efficiency). Finally, in turning dressing, the thermal deformation error, which is called the displacement error, due to the working heat \( Q \) is compensated by the RDLS system.

The paper is organized as follows: first, the structure of the full-aperture lapping turntable based on the RDLS system is described. Second, the bimetal thermal deformation effect is analyzed, based on the thin-plate theory from classical elasticity. The working heat of the full-aperture lapping turntable is investigated. A regression analysis method for the displacement of a lapping pad surface is proposed. Then, the functionality of the RDLS system is tested under various conditions. Finally, orthogonal experiments are conducted to verify the influence of the coolant temperature \( t \) on process performance. We conclude that the method is effective and practical for dressing lapping pad surfaces and the lapping process.

2 Method and theory

2.1 Structure of full-aperture lapping turntable based on the RDLS system

The full-aperture (lapping pad diameter \( d_0 = 1200 \text{ mm} \)) lapping turntable based on the RDLS system consists of a metal-tin lapping pad, an RDLS system, a cast-iron support plate, a turntable mandrel, a turntable bearing, and a torque motor (Fig. 1). The control unit plate in the RDLS system (Fig. 2) and the cast-iron support plate are rigidly connected, and the same material is used for both. An epoxy-resin heat-insulation layer is used to bond the metal-tin lapping pad, and constraint plates in the RDLS system. The lapping turntable is driven by a torque motor to rotate 360° along the \( C \) axis; it is supported in the axial and radial directions by high-precision ball bearings. The surface shape of the lapping pad is deterministically controlled by the RDLS system.

The RDLS system, whose structure is rotationally symmetrical with respect to the \( C \) axis, is composed of a deformation plate, constraint plate, and control unit (Fig. 2). The constraint and deformation plates are solid discs made of metals 1 and 2, respectively (metals 1 and 2 are aluminum alloy and gray cast iron, respectively); their volumes are \( \pi d_1 \times h_1 \) and \( \pi d_2 \times h_2 \), where \( d_1 \) and \( d_2 \) refer to diameter and \( h_1 \) and \( h_2 \) refer to the plate thickness (\( d_1 = d_2 = 1200 \text{ mm}, h_1 = 45 \text{ mm}, h_2 = 25 \text{ mm} \)). The control unit consists of a control unit plate with a cavity structure, circulating cooling water, and a device for water-temperature control. The control unit plate, which is made of metal 2, contains a hollow cavity. The circulating cooling water passes through the cavity; its temperature is controlled by the temperature control device. The temperature fields of

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Fig. 1 Structure of the full-aperture lapping turntable based on the RDLS system: (1) metal-tin lapping pad; (2) support plate (material: cast iron); (3) core shaft; (4) high-precision ball bearings for turntable; (5) torque motor; (6) rotary joint; (7) high-precision water chillers

Fig. 2 Structure of the RDLS system: (1) constraint plate; (2) deformation plate; (3) circulating cooling water; (4) control unit; (5) temperature control device for circulating cooling water; (6) control unit plate
the deformation plate and constraint plate are in turn controlled by the coolant temperature $t$.

The constraint and deformation plates are rigidly connected, and their linear expansion coefficients are different ($\alpha_1 = 23.0 \times 10^{-6}$ 1/K [18], $\alpha_2 = 10.0 \times 10^{-6}$ 1/K [19], where $\alpha_1$ and $\alpha_2$ are the linear expansion coefficients of aluminum alloy and gray cast iron, respectively) Therefore, the different expansion rates as the temperature-field changes result in thermal stress, which causes deformation; this phenomenon is called the bimetal thermal deformation effect. The RDLS system, which is controlled by the parameter $t$, uses this effect to achieve real-time dressing of metal-tin lapping pad surface shape (change in the surface shape of the lapping pad).

### 2.2 The bimetal thermal deformation effect

The principle of the bimetal thermal deformation effect is shown in Fig. 3, where disc 1 and 2 are rigidly connected but made from materials with different linear expansion coefficients $\alpha_a$ and $\alpha_b$. Both discs are assumed to be at the same temperature. The thermal stress generated by the different thermal expansions can be expressed as [20]

$$\sigma_t = \frac{E_2}{(1-v_2)}(\alpha_a - \alpha_b)(T - T_0)$$  

where $\sigma_t$ represents the thermal stress; $E_2$ and $v_2$ are Young’s modulus and Poisson’s ratio of discs 2; $T$ is the current temperature of the discs; and $T_0$ is their initial temperature.

According to the thin-plate thermal deformation theory [21], the flexure deformation of the thin plate is caused by the transverse force in the neutral plane. Let $q_t$ be the equivalent transverse force produced by $\sigma_t$, and $w$ be the flexural deformation for $q_t$. The composite plate is defined as a thin plate composed of discs 1 and 2; a simplified mechanical model is shown in Fig. 3b. The differential equation of the $w$ and $M_p$ is expressed as:

$$D\left(\frac{d^2w}{d\rho^2} + \frac{1}{\rho} \frac{d(\rho^2)w}{d\rho} \right) + \frac{1}{\rho} \frac{d(w)}{d\rho} = q_t$$  

$$M_p = -D\left[\frac{d^2w}{d\rho^2} + \mu\left(\frac{1}{\rho} \frac{d(w)}{d\rho} + \frac{1}{\rho^2} \frac{d^2w}{d\rho^2}\right)\right]$$

where $\rho$ represents the radial distance, and $D$ is the equivalent bending stiffness of the composite plate, $M_p$ is the bending moment, $\varphi$ is the angular position of $w(\rho, \varphi)$ in polar coordinates, and $\mu$ is the equivalent Poisson’s ratio. Equation (2) is an ordinary differential equation, the general solution of which is

$$w = C_1 \ln \rho + C_2 \rho^2 \ln \rho + C_3 \rho^2 + C_4 + \frac{q_t \rho^4}{64D}$$  

where $C_1, C_2, C_3, C_4$ are undetermined coefficients that are solved from the boundary conditions. There is no center hole in the composite plate, therefore $C_1 = 0, C_2 = 0$. Otherwise, in the center ($\rho = 0$), the $w$ and the internal force are infinite. Then, from Eqs. (4) and (3),

$$w = C_3 \rho^2 + C_4 + \frac{q_t \rho^4}{64D}$$  

$$M_p = -2(1+\mu)DC_3 - \frac{3 + \mu}{16} q_t \rho^2$$

The composite plate is assumed to be a simply supported edge. Therefore, the boundary conditions are

$$w(\rho) \big|_{\rho = a} = 0$$  

$$M_p(\rho) \big|_{\rho = a} = 0$$

where $a$ is the radius of the composite plate. From Eqs. (5) and (6),

$$a^2C_3 + C_4 + \frac{q_t a^4}{64D} = 0$$  

$$-2(1+\mu)DC_3 - \frac{3 + \mu}{16} q_t a^2 = 0$$

From Eqs. (9) and (10), $C_3$ and $C_4$ are solved. In summary, $C_1, C_2, C_3,$ and $C_4$ are expressed as

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**Fig. 3** Principle of the bimetal thermal deformation effect: a Two discs, each composed of a different material, viewed as a single composite plate; b transverse force $q_t$ on the composite plate at radial distance $\rho$ leads to flexural deformation $w$.
\[
\begin{align*}
C_1 &= 0 \\
C_2 &= 0 \\
C_3 &= \frac{(3+\mu)q_d a^2}{32(1+\mu)D} \\
C_4 &= \frac{q_d a^2 5\mu}{64D (1+\mu)}
\end{align*}
\tag{11}
\]

The \( w \) is obtained by inserting Eq. (11) into Eq. (4):

\[
w = \frac{q_d a^4}{64D} (1 - \frac{\rho^2}{a^2})(5 + \mu - \frac{\rho^2}{a^2})
\tag{12}
\]

From Eq. (12), the maximum flexural deformation \( w_{\text{max}} \) is at \( \rho = 0 \):

\[
w_{\text{MAX}} = \frac{q_d a^4}{64D} \left( \frac{5 + \mu}{1 + \mu} \right)
\tag{13}
\]

### 2.3 Source analysis of thermal deformation error for the full-aperture lapping turntable

The thermal deformation error is caused by the working heat of the machine tool [22]. The full-aperture lapping turntable based on the RDLS system uses high-precision ball bearings as supporting parts and is directly driven by a torque motor. Therefore, for the full-aperture lapping turntable, \( Q \) is mainly composed of the electromagnetic and frictional heat:

\[
Q = Q_f + Q_e
\tag{14}
\]

where \( Q \) is the working heat of the full-aperture lapping turntable, \( Q_f \) and \( Q_e \) are the friction heat and electromagnetic heat generated by the bearing and the torque motor, respectively.

According to an empirical formula [23], the frictional heat of the ball bearings is expressed as:

\[
Q_f = 1.047 \times 10^{-4} nM
\tag{15}
\]

where \( n \) represents the rotational speed of the bearing inner ring and \( M \) is the frictional torque of the bearings. Because the turntable adopts a direct-drive structure, \( n \) is also the rotational speed of the torque motor and the turntable. The frictional torque \( M \) is due to both the external load and the friction of the bearing. Therefore, \( M \) is expressed as:

\[
M = M_0 + M_1
\tag{16}
\]

where \( M_0 \) and \( M_1 \) are the external load torque and viscous friction torque, respectively. The external load torque \( M_0 \) is expressed as:

\[
M_0 = f_0 k_0 D_m
\tag{17}
\]

where \( f_0 \) is a coefficient determined by the bearing structure, \( k_0 \) represents the equivalent load, and \( D_m \) is the pitch circle diameter of the ball bearing. The viscous friction torque \( M_1 \) is expressed as:

\[
M_1 = \begin{cases} 
10^{-7} f_1 (vn)^{2/3} D_m^3 & \text{if } vn \geq 2000 \\
160 \times 10^{-7} f_1 D_m^3 & \text{if } vn < 2000 
\end{cases}
\tag{18}
\]

where \( f_1 \) is the structure coefficient of the bearing, which is determined by the design and lubrication, and \( v \) represents the kinematic viscosity, which is determined by the lubricant.

The thermal load of the torque motor mainly originates from electromagnetic heat. According to an empirical formula [24], the electromagnetic heat \( Q_e \) of the torque motor is

\[
Q_e = P_{in} \times (1 - \eta_m)
\tag{19}
\]

where \( P_{in} \) is the input power of the torque motor (a function of \( n \)) and \( \eta_m \) represents the working efficiency of the torque motor.

Therefore, from Eqs. (14)–(19), the working heat of the full-aperture lapping turntable (\( Q \)) is finally

\[
Q = P_{in}(n) (1 - \eta_m) + 1.047 \times 10^{-4} n(M_0 + M_1)
\tag{20}
\]

From Eq. (20), when the turntable shaft structure and the external load are constant, the working heat (\( Q \)) depends only on the rotational speed of the torque motor (\( n \)). Therefore, based on the turntable structure and Eq. (20), the calculation and measurement results of \( Q \) are described as shown in Fig. 4. After the turntable ran independently for 70 min (\( n = 100 \) rpm), the temperature at the bottom of the turntable (close to the torque motors and bearings) increased, which was detected by the thermal video system (Fig. 4b). This indicates that the working heat (\( Q \)) was generated. Furthermore, \( Q \) increases with \( n \), which means that the working heat is proportional to the rotational speed of the torque motor (Fig. 4a).

### 2.4 Regression analysis of the displacement of the lapping pad surface

The displacement of the lapping pad surface is generated by thermal deformation caused by the RDLS system and the working heat (\( Q \)). For the rotationally symmetric structure (symmetry axis: \( C \) axis), the displacement curve is used to describe the displacement of the lapping pad surface. From Fig. 5, \( A_1, A_2, \ldots, A_m \) are defined as points on the lapping pad surface, and they are evenly arranged along the radial direction, where \( m \) is the number of points. The thermal deformation will result in the displacement of each point for the lapping pad surface in the \( Z \) direction will be caused. \( \Delta Z_i \) is defined as the displacement of \( A_i \) (\( i = 1, 2, \ldots, m \)) in the \( Z \) direction, which is expressed as:

\[
\Delta Z_i = Z_2 - Z_1, \quad i = 1, 2, 3, \ldots, m
\tag{21}
\]
where $Z1_i$ is the original relative height of the point $A_i$, $Z2_i$ relative height after the deformation, and $Z1_i$ and $Z2_i$ are measured by the laser probe. $\rho_i$ is the distance between point $A_i$ and the C axis. Therefore, the point set $S=\{ (\rho_i, \Delta Z_i), i = 1, 2, \ldots, m \}$ is used to describe the deformation error through the 3rd degree polynomial equation.

Based on the measured data $S=\{ (\rho_i, \Delta Z_i), i = 1, 2, \ldots, m \}$, the following equations can be obtained:

$$\Delta Z_i = \theta_0 + \sum_{i=1}^{n} \theta_i \rho_i + \epsilon$$  \hspace{1cm} (23)

Equation (23) is called a multiple-linear regression equation. From the point set $S=\{ (\rho_i, \Delta Z_i), i = 1, 2, \ldots, m \}$ and Eq. (23), the following equations can be obtained:

$$\begin{align*}
\Delta Z_1 &= \theta_0 + \theta_1 \rho_1 + \theta_2 \rho_1^2 + \ldots + \theta_n \rho_1^n + \epsilon \\
\Delta Z_2 &= \theta_0 + \theta_1 \rho_2 + \theta_2 \rho_2^2 + \ldots + \theta_n \rho_2^n + \epsilon \\
& \quad \ldots \\
\Delta Z_m &= \theta_0 + \theta_1 \rho_m + \theta_2 \rho_m^2 + \ldots + \theta_n \rho_m^n + \epsilon
\end{align*}$$  \hspace{1cm} (24)

Let $x_1 = \rho, x_2 = \rho^2, \ldots, x_n = \rho^n$. Then, Eq. (22) can be transformed into

$$\Delta Z(x_1, x_2, \ldots, x_n) = \theta_0 + \sum_{i=1}^{n} \theta_i x_i + \epsilon$$  \hspace{1cm} (23)

where $\Delta Z(\rho)$ is the displacement in $Z$ direction, $\theta_1, \theta_2, \ldots, \theta_n$ are undetermined coefficients, $\rho$ is the distance, $\epsilon$ is random error. Based on the measured data $S=\{ (\rho_i, \Delta Z_i), i = 1, 2, \ldots, m \}$, $\theta_1, \theta_2, \ldots, \theta_n$ are solved using the regression analysis.

Let $x_1 = \rho, x_2 = \rho^2, \ldots, x_n = \rho^n$. Then, Eq. (22) can be transformed into

$$\Delta Z(x_1, x_2, \ldots, x_n) = \theta_0 + \sum_{i=1}^{n} \theta_i x_i + \epsilon$$  \hspace{1cm} (23)

The undetermined coefficients $\{ \theta_0, \theta_1, \ldots, \theta_n \}$ are given by Eq. (25), and the displacement model of the lapping pad surface $\Delta Z(\rho)$ can be obtained by inserting them into Eq. (22).

### 2.5 Multi-parameter optimization method

#### 2.5.1 Lapping process evaluation criteria

The material removal rate (MRR) and surface change uniformity (SCU) are important evaluation criteria for the lapping process of plane optical elements. Based on the Preston equation [26], MRR is expressed as:

$$MRR = \frac{\Delta Z}{t}$$
\[ MRR = \frac{\Delta h}{\Delta t} \]  
(26)

where \( \Delta h \) is material removal height in unit time. In the lapping processing, the quality change of the optical component is measured, and it is used to calculate the MRR. Let \( m_i \) is the weight of the optical element after the \( i \)th experiment, \( \rho_c \) is the material density of the optical element, \( t_c \) represents the lapping time of each experiment, and \( s_i \) is the processing area of the optical component. Therefore, according to Eq. (26), \( MRR \) is expressed as:

\[ MRR_i = \frac{m_i - m_{i-1}}{\rho_c \cdot s_c \cdot t_c}, \quad i = 1, 2, 3, ..., c \]  
(27)

where \( MRR_i \) represents the MRR of the \( i \)th experiment, \( c \) represents the number of experiments, and \( m_0 \) is the initial quality of the optical element.

The SCU is defined as the change uniformity of the optical element surface after processing. Here \( B_i \) is the \( i \)th point on the processing surface of the optical component. The SCU is expressed as:

\[ SCU = \sqrt{\frac{1}{l} \sum_{i=1}^{l} (\Delta y_i - y_0)^2} \]  
(28)

where \( \Delta y_i = y_2i - y1i \), \( y1i \) is the relative height of the point \( B_i \), \( y2i \) is the relative height after processing, \( y1i \) and \( y2i \) are measured by a laser interferometer, \( l \) is the number of points, and \( y_0 \) is the reference height, determined by \( \Delta y_i \).

The grinding, lapping, and polishing are an important manufacturing process for high-precision plane optical components with specific purposes. In the grinding process, it is necessary that a satisfactory surface shape is obtained. Therefore, in this stage, the surface morphologies and surface roughness are used as the main evaluation criterion. For example, Li et al. investigated the surface morphology and roughness of GGG single crystals in the grinding and proposed their prediction models [27, 28]. For the lapping process, the surface shape accuracy needs to be further improved. The MRR and SCU are important evaluation criteria at this stage. Generally, for the processing efficiency and surface accuracy, larger MRR and smaller SCU are expected. Therefore, it is necessary to optimize the process parameters to obtain better MRR and SCU.

### 2.5.2 Orthogonal experiment and range analysis

The orthogonal experiment is a research method that is used for parameter optimization and analysis [29]. Compared to the complete experimental method, a part of the experiment combinations that is based on an orthogonal table, is used in the experiments. Then, based on the experimental results, the range analysis method is used to analyze the impact of factors and optimize the parameters. Here \( u \) is defined as the number of factors; \( v \) is defined as the number of levels. Therefore, for the experiments of \( u \) factors and \( v \) levels, \( L_u(v) \) orthogonal table is selected, and its selection principles are as follows:

\[
\begin{align*}
    c & \geq \sum_{k \geq u} (v - 1) + 1 \\
    & \text{for all factors}
\end{align*}
\]  
(29)

where \( k \) is the number of factors that can be arranged in the orthogonal table, \( c \) is the number of experiments.

The range analysis method is used to analyze the results of orthogonal experiments. In \( L_u(v) \) orthogonal experiment, \( K_{ij} \) is defined as the average of the experimental results for the \( i \)th level under the \( j \)th factor, which is expressed as:

\[ K_{ij} = \frac{A_{ij}}{R} \]  
(30)

where \( A_{ij} \) represents the sum of all experimental results for the \( i \)th level under the \( j \)th factor and \( R \) is the number of experimental results for the \( i \)th level under the \( j \)th factor. \( K_{ij} \) describes the magnitude of the experimental results at the \( i \)th level. Therefore, the parameters are optimized by comparing \( K_{ij} \).

\( R_j \) is defined as the range of the \( j \)th factor, which is expressed as:

\[ R_j = \max(\bar{K}_{ij}, \bar{K}_{2j}, ..., \bar{K}_{uj}) - \min(\bar{K}_{ij}, \bar{K}_{2j}, ..., \bar{K}_{uj}), \quad j = 1, 2, ..., u \]  
(31)

\( R_j \) is used to evaluate the influence degree of the \( j \)th factor on the experimental results. The larger the value of \( R_j \), the greater the influence of the \( j \)th factor on the experimental results.

### 3 Experimental program

#### 3.1 Measurement of the displacement of the lapping pad surface

The experiments were designed to measure the displacement of the lapping pad surface controlled by the RDLS system (control parameter \( t \)) and the working heat (\( Q \) (control parameter \( n \)). The measurement scheme is described, as shown in Fig. 6. The turntable shaft was driven by a torque motor with 360° rotation along the \( C \) axis. The laser sensor (Model: LK-H020, Keyence Corporation), which was fixed on the dressing shaft, was controlled to move linearly along the \( X \) axis. Through the movement (\( X \) direction) of the laser
sensor, the displacement data of the lapping pad surface is acquired. Finally, according to Eq. (21), the displacement of the lapping pad surface is calculated. Four sets of experiments were implemented to analyze the displacement under different conditions.

3.1.1 Experiment 1: Rules of the change of lapping pad surface over time $\tau$

Experiment 1 is carried out to analyze the law of the surface shape of the lapping pad and $\tau$, where $\tau$ is the running time of the RDLS system (or the turntable). $Z_i(\tau)$ is defined as the relative height of the point $A_i$ after the RDLS system (or the turntable) runs for $\tau$ time, which is measured by a laser probe. The point set $\{ (\rho_i, Z_i(\tau)) | i = 1, 2, ..., m \}$ describes the surface shape of the lapping pad at time $\tau$. In conditions 1 and 2, the surface shape of the lapping pad is measured at $\tau = 20, 40, 60, \text{ and } 80$ min, which is compared and analyzed in Sect. 4.1. The parameters of experiment 1 are shown in Table 1.

3.1.2 Experiment 2: Displacement error for the lapping pad surface caused by the working heat

The displacement of the lapping pad surface caused by the working heat ($Q$), which is also called the displacement error, is tested in experiment 2. According to Sect. 2.3, the working heat ($Q$) is determined with the rotational speed of the turntable ($n$). Generally, in the lapping processing, the rotation speed ($n$) is less than or equal to 20 rpm, and in the turning dressing, it is equal to 100 rpm. Therefore, the displacement error of the lapping pad surface is measured and analyzed at $n = 20, 60, \text{ and } 100$ rpm respectively. $\Delta Z_i(n)$ is defined as the displacement error of point $A_i$, which is expressed as:

$$\Delta Z_i(n) = Z_i(n) - Z_1,$$  \hspace{1cm} (32)

where $Z_i(n)$ is the relative height of point $A_i$ after the turntable works at $n$ rotational speed for $\tau_0$ time and $Z_1$ is the original relative height of point $A_i$. $\tau_0$ is the standard running time of the RDLS system or the turntable in each experiment. The point set $\{ (\rho_i, \Delta Z_i(n)) | i = 1, 2, ..., m \}$ describes the displacement error of the lapping pad surface. When the turntable rotates at a high speed, it is difficult to measure the displacement of the lapping pad surface. Therefore, it is necessary to stop the turntable first (stop at the initial angular position every time) and then measure the displacement immediately. To ensure the accuracy of the data, the working time of the turntable is $\tau_0$ before each measurement.

EPV is called the peak-to-valley (PV) deviation of the displacement error, which is used to evaluate the magnitude of the displacement error. It is expressed as:

$$EPV = \max_{i=1,2,...,m} (\Delta Z_i(n)) - \min_{i=1,2,...,m} (\Delta Z_i(n)) \hspace{1cm} (33)$$

The larger the EPV, the larger the displacement error, and vice versa. To improve the accuracy of turning dressing, a smaller displacement error is expected. Therefore,
the smaller EPV, the better. The experimental parameters are shown in Table 2. According to Eqs. (32) and (33), the results of the experiment are analyzed in Sect. 4.2.

3.1.3 Experiment 3: Real-time dressing of the lapping pad surface based on the RDLS system

The displacement of lapping pad surface caused by the RDLS system is called the correction displacement, and it helps achieve real-time dressing of the lapping pad surface; this was studied in experiment 3. $\Delta Z_i(t)$ is defined as the correction displacement of point $A_i$, which is expressed as:

$$\Delta Z_i(t) = Z_i(t) - Z_{i1}$$

(34)

where $Z_i(t)$ is the relative height of point $A_i$ after the RDLS system (the coolant temperature is $t$) and turntable ($n = 20$ rpm) runs for $\tau_0$ time simultaneously. The point set $\{(\rho_i, \Delta Z_i(t)) | i = 1, 2, ..., m\}$ describes the correction displacement of the lapping pad surface.

Under the influence of the correction displacement, the flatness of the lapping pad surface will also change. According to ISO 12781–1, peak-to-valley (PV) flatness deviation and root mean square (RMS) flatness deviation are the commonly used evaluation indicators of flatness [30]. Here, FPV and FRMS are the PV flatness deviation and RMS flatness deviation of the lapping pad surface, respectively, and they are expressed as:

$$FPV = \max_{i = 1, 2, ..., m} (\Delta Z_i(t)) - \min_{i = 1, 2, ..., m} (\Delta Z_i(t))$$

(35)

$$FRMS = \sqrt{\frac{\sum_{i=1}^{m} (\Delta Z_i(t) - \Delta Z_0(t))^2}{m}}$$

(36)

where $\Delta Z_0(t) = \frac{\sum_{i=1}^{m} \Delta Z_i(t)}{m}$. Under the rotational speed of the turntable $n = 20$ rpm, the correction displacement of the lapping pad surface is measured at the control parameters of the RDLS system $t = 16, 17, 18, 19, 20$ °C. The experimental parameters are shown in Table 3. The results of the experiment are analyzed by Eqs. (34)–(36) in Sect. 4.3.

3.1.4 Experiment 4: The displacement error compensation based on the RDLS system

Experiment 4 is designed to verify the compensation ability of the RDLS system on the thermal deformation displacement error. At the rotational speed of the turntable $n = 100$ rpm, the displacement error of the lapping pad surface is measured when the control parameters of the RDLS system $t = 16, 17, 18, 19, 20$ °C. The experimental parameters are shown in Table 4. The calculation and analysis of the experimental results are given by Eqs. (32) and (33), in Sect. 4.4.

3.2 Process optimization experiment based on parameter $t$

The coolant temperature $t$ of the RDLS system can be adjusted in real-time during the lapping processing;

| Table 3 | Parameters of experiment 3 |
|---------|----------------------------|
| $t$ (°C) | $n$ (rpm) | The correction displacement and flatness of the lapping pad surface |
| 16      | 20        | $\Delta Z_i(t) = Z_i(t) - Z_{i1}$, FPV, FRMS |
| 17      | 20        | |
| 18      | 20        | |
| 19      | 20        | |
| 20      | 20        | |

| Table 4 | Parameters of experiment 4 |
|---------|----------------------------|
| $t$ (°C) | $n$ (rpm) | The displacement error of the lapping pad surface |
| 16      | 100       | $\Delta Z_i(n) = Z_i(n) - Z_{i1}$, $EPV = \max_{i = 1, 2, ..., m} (\Delta Z_i(n)) - \min_{i = 1, 2, ..., m} (\Delta Z_i(n))$ |
| 17      | 100       | |
| 18      | 100       | |
| 19      | 100       | |
| 20      | 100       | |
therefore, the parameter $t$ can be used for process optimization. The influence of parameter $t$ on the process performance of the plane optical component was verified by the experiments described below.

The coolant temperature of the RDLS system ($t$), the rotation speed of the lapping turntable ($n$), and the lapping pressure ($P$) were set as the process parameters for the process optimization experiments. The process parameters $t$, $n$, and $P$ are adjusted using precision water chiller 1, torque motor, and weights, respectively. The experimental scheme and settings are shown in Fig. 7 and Table 5, respectively.

Using the process parameters $t$, $n$, and $P$, three-factor and three-level process optimization experiments were designed, as shown in Table 6. To improve the efficiency of the experiment, the orthogonal experiment method was adopted to design a combination of each group of experiments. According to Sect. 2.5.2, the $L_9(3^4)$ orthogonal table proposed by Taguchi [31] was used to arrange each group of experiments. Material removal rate (MRR) and surface change uniformity (SCU) were selected to evaluate the results of each set of experiments. Experimental results can be obtained according to Eqs. (27) and (28).

### 4 Results, discussion, and analysis

#### 4.1 The rules of the displacement of lapping pad surface over time $\tau$

The results of experiment 1 were described in Fig. 8, which shows the rules between the surface shape of the lapping pad and time $\tau$.

Under condition 1 (the RDLS system worked independently, $t = 19 \, ^\circ\text{C}$), the surface shape of the lapping pad is changed, which means that the new surface shape is obtained for the lapping pad. This shape is different from the initial surface shape, as shown in Fig. 8a. Furthermore, the new surface shape is constantly changing over time $\tau$. However, when $\tau \geq 60 \, \text{min}$, the shape remained the same, which means that a new surface shape that is stable and does not change over time is obtained. Similarly, under condition 2 (the turntable ran independently, $n = 100 \, \text{rpm}$), there are similar conclusions that when the working time ($\tau$) of the turntable is greater than 60 min, a new stable surface shape will be obtained for the lapping pad, as shown in Fig. 8b.

In summary, the change of the lapping pad surface shape is caused by the RDLS system or the working heat ($Q$), which is called the displacement of the lapping pad surface. When $\tau \geq 60 \, \text{min}$, a new surface shape of the lapping pad is obtained, which is stable and does not change over time.

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**Table 5** Parameter settings of process optimization experiment

| Name   | Lapping pad | Component type | Component volume | Slurry | Environment and slurry temperature |
|--------|-------------|----------------|------------------|--------|-----------------------------------|
| Value  | Metal-tin pad | Fused silica   | $\pi \times 140 \times 40 \, \text{mm}^3$ | $\text{Al}_2\text{O}_3$ (concentration 1.2%) | $21 \pm 0.5 \, ^\circ\text{C}$ |

**Table 6** Factors and levels of optimization experiments

| Levels | Factors | $t$ | $n$ | $P$ |
|--------|---------|-----|-----|-----|
| 1      |          | $16 \, ^\circ\text{C}$ ($t_1$) | 8 rpm ($n_1$) | 1 kPa ($P_1$) |
| 2      |          | $18 \, ^\circ\text{C}$ ($t_2$) | 4 rpm ($n_2$) | 2 kPa ($P_2$) |
| 3      |          | $20 \, ^\circ\text{C}$ ($t_3$) | 12 rpm ($n_3$) | 4 kPa ($P_3$) |

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**Fig. 8** Surface shape of the lapping pad for two typical conditions: a RDLS system works independently (at $t = 19 \, ^\circ\text{C}$); b turntable runs independently (at $n = 100 \, \text{rpm}$)
Therefore, the value $\tau_0 = 70$ min was used in the following experiments.

### 4.2 Displacement error for the lapping pad surface caused by the working heat $Q$

The results of experiment 2 are shown in Fig. 9, which describes the displacement error of the lapping pad surface in different situations.

From Fig. 9c, under the rotational speed of the turntable $n = 20$ rpm, the PV deviation of the displacement error (EPV) is approximately equal to 0 ($EPV = 1.36 \, \mu m$), which means that there were no displacement errors of the lapping pad surface. However, as $n$ increased, so did the EPV, which means that as the rotational speed of the turntable ($n$) increased, the displacement error also increased, and when $n = 100$ rpm, the displacement error is the largest ($EPV = 21.2 \, \mu m$). Secondly, the change trend of the displacement error is shown in Fig. 9a. When $n = 20$ rpm, the displacement error of each point is basically the same. However, there are different trends for $n = 60$ or $100$ rpm that the displacement error of each point increased linearly as $\rho$ increased. Finally, according to Sect. 2.4, based on regression analysis, the displacement error models are expressed as:

$$\Delta Z(n, \rho) = \begin{cases} 
0.0029\rho + 7.704 & n = 20 \text{rpm} \\
0.0198\rho + 6.020 & n = 60 \text{rpm} \\
0.0466\rho + 3.336 & n = 100 \text{rpm} 
\end{cases} \quad (37)$$

where $\Delta Z(n, \rho)$ is called the displacement error model for the lapping pad surface, as shown in Fig. 9b.

To obtain plane optical elements, both the turning dressing of the lapping pad surface and the lapping processing of the plane element are important. The rotational speed of the turntable ($n$) is usually set as less than 20 rpm and 100 rpm during lapping and turning correction, respectively. Thus, in the lapping processing for the optical elements ($n \leq 20$ rpm), the displacement error of the lapping pad surface, which is caused by $Q$, is approximately 0, and it can be uncompensated. By contrast, in the turning dressing for the lapping pad ($n = 100$ rpm), the displacement error is the largest ($EPV = 21.2 \, \mu m$), which must be compensated; Eq. (37) can be used for compensation, and which can also be called the compensation equations.

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**Fig. 9** The displacement error of the lapping pad surface after the turntable ran independently for 70 min: a Thermal deformation error curves for the lapping pad surface at 20, 60, and 100 rpm; b regression analysis for the thermal deformation error curves; c calculation result of EPV
4.3 The dressing of the lapping pad surface based on the RDLS system

Based on the results of experiment 3, the correction displacements (real-time dressing), controlled by the RDLS system, which are analyzed, as shown in Fig. 10.

First, from Fig. 10c, for the lapping pad surface, FPV and FRMS are affected by the RDLS system, which can be optimized by adjusting the coolant temperature ($t$). Under the initial surface shape used in the experiments of this section ($FPV = 33.90 \mu m$, $FRMS = 8.1 \mu m$), the optimal flatness of the lapping pad surface is obtained at $t = 20 ^\circ C$, in which FRMS and FPV are 5.23 and 17.68 $\mu m$ respectively. Secondly, there are different trends for the correction displacements under different values of $t$. According to Fig. 10a, under $t = 16 ^\circ C$, from distance $\rho = 100–300$ mm, the correction displacement was maximal; and from $\rho = 300–500$ mm, the correction displacement decreased as the $\rho$ increased; and then the correction displacement remained unchanged from 500–590 mm. At $t = 17 – 20 ^\circ C$, the same trends for the correction displacements of the lapping pad surface are observed; as $\rho$ increased (from 100 to 600 mm), the correction displacement decreased. Finally, as stated in Sect. 2.4, the correction displacements model, which is called the real-time dressing models, is expressed as:

$$\Delta Z(t, \rho) = \begin{cases} 
(1.63e-9)\rho^4 - (2.05e-6)\rho^3 + (8.47e-4)\rho^2 - (1.41e-1)\rho + 14.96 & t = 16 ^\circ C \\
(1.47e-9)\rho^4 - (1.86e-6)\rho^3 + (7.55e-4)\rho^2 - (1.30e-1)\rho + 20.63 & t = 17 ^\circ C \\
(1.24e-9)\rho^4 - (1.57e-6)\rho^3 + (6.03e-4)\rho^2 - (9.8e-2)\rho + 23.43 & t = 18 ^\circ C \\
(1.35e-9)\rho^4 - (1.76e-6)\rho^3 + (6.83e-4)\rho^2 - (1.10e-1)\rho + 28.35 & t = 19 ^\circ C \\
(1.20e-9)\rho^4 - (1.57e-6)\rho^3 + (5.75e-4)\rho^2 - (8.52e-2)\rho + 28.49 & t = 20 ^\circ C 
\end{cases}$$

Fig. 10 The correction displacement (real-time dressing) curves during lapping processing at $n = 20$ rpm for various coolant temperature $t$: a the correction displacement of the lapping pad surface at $t = 16, 17, 18, 19,$ and $20 ^\circ C$; b regression analysis for the correction displacement; c FPV and FRMS calculation results
where $\Delta Z(t, \rho)$ is the real-time dressing model for the RDLS system, as shown in Fig. 10b.

In summary, during the lapping processing ($n \leq 20$ rpm), through the correction displacement, the real-time dressing of the lapping pad surface is realized. By adjusting the coolant temperature $t$ of the RDLS system, different correction displacements could be obtained. The flatness can also be optimized with the RDLS system. In addition, according to Eq. (38), the surface shape after real-time dressing can be predicted.

### 4.4 The displacement error compensation based on the RDLS system

Based on the scheme of experiment 4, the displacement error is compensated by the RDLS system, whose results are shown in Fig. 11.

From Fig. 11b, as the coolant temperature ($t$) of the RDLS system increased, the PV deviation of the displacement error after compensation (EPV) first decreased and then increased. At $t = 19$ °C, the smallest EPV was obtained ($EPV = 5.13 \mu m$), which means that the displacement error was the smallest. It can be seen that through the RDLS system, EPV has decreased from 21 μm (without compensation) to 5 μm ($t = 19$ °C). Therefore, the displacement error, which is caused by $Q$, was effectively compensated by the RDLS system. Secondly, it can be seen from Fig. 11a that at $t = 19$ °C, a slight displacement error is also generated. Compared to the displacement error without compensation, the displacement error ($t = 19$ °C) slowly increased first from $\rho = 100–330$ mm and then slowly decreased from $\rho = 330–600$ mm.

In summary, during turning dressing ($n = 100$ rpm), the displacement error for the working heat ($Q$) was compensated by the RDLS system. At $t = 19$ °C, the smallest displacement error of the lapping pad surface occurred.

### 4.5 Process parameter optimization based on control parameter $t$

The combination and measurement results of the orthogonal experiments are listed in Table 7.

The results of the range analysis are shown in Fig. 12 and Table 8. First, the MRR and SCU were affected by the control parameter ($t$) of the RDLS system, as shown in Figs. 12a, b: they increased with an increase in $t$. Secondly, from Table 8, ranges ($R_j$) of the three factors ($t$, $n$, and $P$) for MRR were 85, 100, and 197 nm/h, $R_j$ for SCU were 7, 15, and 18 nm, respectively. Therefore, $P$ was the factor with the most influence on MRR and SCU, and $t$ the factor with the least. Finally, the optimal combinations for MRR and SCU are analyzed by the range method. A larger MRR and smaller SCU are expected. From Table 8, for MRR, the $K_{ij}$ of factors were the largest at level 3; therefore, the optimal parameter combination was $t_3n_3P_3$ for MRR. Similarly, for SCU, the smallest $K_{ij}$ for factors were acquired at levels 1, 2, and 1 respectively, and $t_1n_2P_1$ was the best combination for SCU.

![Fig. 11](image) Displacement error after compensation: a the displacement error compensated by the RDLS system; b EPV calculation results at $t = 16, 17, 18, 19$, and 20 °C

![Table 7](image) $L_9(3^4)$ orthogonal experimental design and results

| No. | Factor | MRR (nm/h) | SCU (nm) |
|-----|--------|------------|----------|
| 1   | $t_1$  | $n_1$      | $P_1$    |
| 2   | $t_1$  | $n_2$      | $P_2$    |
| 3   | $t_1$  | $n_3$      | $P_3$    |
| 4   | $t_2$  | $n_1$      | $P_2$    |
| 5   | $t_2$  | $n_2$      | $P_3$    |
| 6   | $t_2$  | $n_3$      | $P_1$    |
| 7   | $t_3$  | $n_1$      | $P_3$    |
| 8   | $t_3$  | $n_2$      | $P_1$    |
| 9   | $t_3$  | $n_3$      | $P_2$    |
To verify the validity of the optimization results, supplementary experiments for the optimal combination were conducted. The experimental results for the optimal combinations were presented in Table 9, which shows that compared with the 9 sets of results in an orthogonal table $L_9(3^4)$, the best results of MRR and SCU are obtained through the optimal combination of parameters.

Based on the above experiment and analysis, the control parameter $t$ of the RDLS system can be set as a process parameter to optimize the MRR and SCU.

### 5 Conclusion

The RDLS system based on the bimetal thermal deformation effect was proposed to realize real-time dressing of the lapping pad surface shape. The working heat of the full-aperture turntable ($Q$) was analyzed. Experimental and theoretical analyses of the RDLS system led to the following conclusions:

1. The displacement for the lapping pad surface was caused by the RDLS system and the working heat ($Q$), which is stable at working times $\tau \geq 60$ min.
2. During the turning dressing of the lapping pad ($n = 100$ rpm), the displacement error, which is caused by the working heat ($Q$), should be compensated. During the lapping processing for optical elements ($n \leq 20$ rpm), the displacement error is small, and it can be left uncompensated.
3. In turning dressing ($n = 100$ rpm), the displacement error can be compensated by the RDLS system, which is smallest at $t = 19$ °C. In the lapping process ($n \leq 20$ rpm), the real-time dressing of the lapping pad surface shape can be achieved by the correction displacement which controlled by the RDLS system.
4. The coolant temperature ($t$) of the RDLS system, which is a process parameter, can be used for process optimization. Both the MRR and SCU are affected by the coolant temperature ($t$). The best results for MRR and SCU were obtained by $t_3n_3P_3$ and $t_1n_2P_1$, respectively.

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### Author contribution
Conceptualization, L. Z., H. Z., and R. X.; methodology, L. Z., H. Z., and R. X.; formal analysis, L. Z. and H. W.; investigation, L. Z., M. C., M. Z., and S. Z.; writing-original draft preparation, L. Z.; writing-review and editing, H. Z., H. W., and S. Z.

### Declarations

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