Analysis of the optical quartz lens centering process based on acoustic emission signal processing and the support vector machine

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Abstract
A method was proposed for analyzing the optical glass lens centering process, and experiments on biplane quartz lenses were performed to determine the material removal rate (MRR) for the hard, brittle material. This study used acoustic emission-sensing technology to monitor the MRR and reconstruct the original shape of the lens. The MRR was evaluated, and an error of 17.87% was obtained. A Taguchi experiment was combined with signal analysis to optimize the process parameters, and a support-vector machine was trained to classify the quality of the grinding wheel; the model had accuracy 98.8%. By using the proposed analysis method, workpiece quality was controlled to an edge surface roughness of < 2 μm, a lens circularity error of < 0.01 mm, a crack length of < E0.1, and an optical axis error of < 150 μrad.

Keywords Centring · Biplane quartz lens · Grinding wheel wear · AE signal · Material removal · SVM

1 Introduction
Biplane quartz lenses are a crucial auxiliary material in semiconductor manufacturing processes. Because it has high purity (impurity < 10 ppm), a low thermal expansion coefficient (5.11–5.8 ×10⁻⁷/K), high-temperature resistance (softening point of approximately 1700 °C), high resistance to acids and alkalis, a low refractive index (1.45), low dispersion (Abbe number =68), and good light transmittance in the infrared to ultraviolet bands, quartz is often used in experimental equipment and high-precision measuring instruments. In biplane quartz lens manufacturing processes, centering, which minimizes the optical axis error, is a key procedure. Centering process is the process to center the lens optical axis and shape the lens edge based on grinding process. The process adjusts a lens mechanical axis to be coincident with the optical axis.

Grinding, abrasive waterjet, wire sawing, and laser cutting are general quartz cutting methods. Quartz is a hard-and-brittle material with 820 HK of Knoop hardness, which is about 6.8 times of aluminum. The cutting ability of waterjet is affected by the flow rate, and the surface quality decreases with the cutting depth [1], while wire sawing may cause cracks around the cutting surface. Thus, the two methods are suitable for situations with no special requirement for surface quality, such as cutting large blanks or thin plates. High-power lasers are required for cutting quartz due to 1700 °C of high melting point. Although the surface quality of laser cutting is better than tool cutting, it is prone to thermal damage [2]. Therefore, compared to the aforementioned wire-cutting method, grinding is the most suitable processing method that can simultaneously meet the specifications and imaging quality required by quartz in optical lenses. However, the complex grinding mechanism and interference from cutting fluids and machine make the centering process difficult to monitor. The prevention of surface burn, thermal damage, cracking, and subsurface damage on workpieces is highly important since these damages decrease the quality of workpieces. Tool wear is an inevitable phenomenon that causes workpiece damages. Because of the complex and rapid wear mechanism of grinding wheels, wear monitoring becomes a challenging task [3–6].

Because of a lack of real-time monitoring methods, qualities such as the optical axis and the presence of cracks and
scratches cannot be observed until the centering process is complete. To solve this problem, acoustic emission (AE) sensors can be applied to monitor the machining process. In the grinding process, AE signals are employed to monitor material removal [7–9], grinding wheel wear [10], chip loading [11–13], and the dressing of the grinding wheel [14]. The root mean square (RMS) of the amplitude of the AE signal is a useful reference value for analyzing time-domain features [15]. The surface of a processed material can be evaluated using an AE polar map in ultraprecision turning [16]. The frequency characteristics of AE signals are obtained through fast Fourier transform (FFT) analysis [17, 18]. Wavelet analysis is a suitable method for locally analyzing both the frequency and time domains [19–22]. The time and frequency features of signals can be used as reference parameters of a support vector machine (SVM) to perform binary classification that helps judging certain conditions, such as end point detection [23], tool breakage [24], grinding burns [25–27], and surface roughness monitoring. [28–30]. SVM is a learning algorithm of classification and regression analysis based on supervised learning model. It builds a classifier in space to assign new examples to one or the other category. In complicated situations, SVMs are used to classify multiple classes through a series of steps [31].

In this study, a Taguchi experiment was designed in which the process parameters were used as the input factors for evaluating the influence of each factor on lens quality. The ideal process conditions were determined in advance on the basis of the results of the experiment. AE sensors were applied to monitor the amount of lens material removed by the grinding wheel. A wavelet analysis was performed to decompose the AE signals into seven detailed layers, which indicated the distribution of the signal frequency bands, and the energy ratio of each layer was extracted.

This study created a monitoring and analysis methods for the centering process after conducting a series of experiments. By accumulating AE signals in the angular domain, the removal amount of material is derived from the lens, and the original shape could then be inversely calculated. Material removal monitoring and shape reconstruction can be applied to different workpiece by taking lens material and geometry into consideration. Moreover, an SVM model was created to evaluate the wear caused by the grinding wheel by classifying grinding wheel condition into “normal” or “worn.”

2 Experimental methods

2.1 Grinding material removal rate

The cylindrical grinding mechanism in the centering process consists of two stages: the feed and spark-out. Figure 1 presents a schematic of the cylindrical grinding mechanism. During the feed stage, the grinding wheel is implemented until the desired outer diameter of the lens is achieved. The spark-out procedure ensures the roundness of lens. The grinding wheel stops feeding, and material is removed through rotation of the lens and grinding wheel.

The material removal rate (MRR) \( u \) is expressed as follows: [32]

\[
\begin{align*}
    u &= b_w \times a_e \times v_w, \\
    a_e &= v_f \times t, \\
    a_e &= v_f \left( t - \frac{k - 1}{n_w} \right),
\end{align*}
\]

where \( b_w \) is the grinding width, \( a_e \) is the effective grinding depth, and \( v_w \) is the horizontal speed of the workpiece.

In general, the feed rate and rotational speed of the workpiece are fixed during one stage of grinding. If the grinding wheel and workpiece remain in contact, the cutting depth should be the same as the grinding wheel infeed, which stably increases as a function of time. When grinding wheel wear is ignored, \( a_e \) is expressed as follows:

\[
    a_e = v_f \times t,
\]

where \( v_f \) is the feed rate of the grinding wheel and \( t \) is the feeding time.

If the lens is rotated several times in one stage, the cutting depth of previous rotations should be subtracted from the total feed as follows:

\[
    a_e = v_f \left( t - \frac{k - 1}{n_w} \right),
\]

where \( n_w \) is the rotation frequency of the workpiece in rpm and \( k \) is the number of rotations.

A double-plane mirror was manufactured from a square quartz block. Centering is the key process in trimming the
outer edge to a circular shape. The diameter of the biplane quartz lens after grinding was 37.65 mm. Figure 2 presents the biplane quartz lens.

The material removal process is divided into two states based on the geometry of the lens and the grinding process: intermittent removal and continuous removal. Three circles were marked on the polished surface of the lens (Fig. 3):

1. Holding circle: the diameter of the circle is the holder diameter. The holding force directly affects the number of scratches on the polished surface of the lens.
2. Desired diameter: the final diameter of the lens set by the working parameters.
3. Cylindrical grinding circle: the material removal process changes from intermittent removal to continuous removal. Cylindrical grinding starts as the grinding wheel reaches the cylindrical grinding circle.

The effective cutting depth varies each time because the contact between the lens and grinding wheel is discontinuous. Because the timing of the cut-in and cut-out at each corner is difficult to determine, AE sensors are used to monitor the contact between the lens and grinding wheel.

Figure 4 presents the details of the lens removal process. Because the lens is rotated about the work axis, the contour of the lens during grinding consists of several concentric circles continuously shrinking inward. The grinding wheel is assumed to make contact with the lens at corner 1. When corner 2 is rotated to the far right, the grinding wheel covers a horizontal distance \( \frac{15\omega f}{60} \) (mm), where \( f \) is the infeed rate in mm/s and \( \omega \) is the lens rotation speed in rpm. When corner 3 is rotated to the far right, the grinding wheel covers \( \frac{30f}{60} \) (mm), and so on. The nth time a certain corner of the lens is ground, the total feed of the grinding wheel is \( \frac{15nf}{60} \) (mm). An arrow-shaped area of the corner is removed, and the central length of the arrow-shaped area is the distance that the grinding wheel has traveled.

The area removed increases as each corner is rotated to the grinding point (Fig. 4a–e). When corner 2 is rotated to the grinding point for a second time, the part that has already been removed should be deducted. If the length of the lens is \( l \) (mm), depending on the geometry of the lens, the grinding wheel advances \( l \left( \frac{f}{\sqrt{2}} - \frac{1}{2} \right) \) (mm) from the contact point and reaches the cylindrical grinding circle. Then, the grinding wheel and the lens remain in contact, and the continuous removal begins (Fig. 4h).

Depending on the signal graph in the time domain, the AE signal increases in intensity as the amount of material removed increases, and the periodic peaks gradually turn into plateaus. When the grinding wheel advances to the cylindrical grinding circle, the signal waveform gradually stabilizes (Fig. 4j).
2.2 Signal analysis

In the wavelet analysis, the original signal $w(t)$ is decomposed into different time and frequency scales by the scaled and translated mother wavelet as follows:

$$W(a, b) = \frac{1}{\sqrt{|b|}} \int_{-\infty}^{\infty} w(t) \psi(\frac{t-a}{b}) dt$$

(4)

where $\psi(t)$ is the mother wavelet, $a$ is the translation of the function in time domain, and $b$ is the scaling factor.

The time range covered by the mother wavelet can be modified by zooming. As the time range is longer, the mother wavelet changes more slowly, corresponding to lower frequency. The property of multi-resolution makes wavelet analysis good for local analysis in both frequency and time domain. Therefore, the AE signal characteristics extracted by wavelet analysis can be well applied to monitor abnormal phenomena during processing.

Daubechies wavelet, Biorthogonal wavelet, Symlets wavelet, and Coiflets wavelet are common mother wavelets [33]. In this study, the Daubechies wavelet is chosen as the mother wavelet due to its advantage in signal reconstruction and denoising.

AE signals were decomposed into one approximate layer and seven detailed layers of different frequency bands. The detailed layers are the data extracted from the original data with the time segments from high frequency to low frequency. The approximate layer is the residual signals after the detailed layers were subtracted from the original data. Figure 5 presents the results of the signal decomposition.

Figure 6 presents the data classification of the SVM model. “Normal” and “worn” wheels are indicated by +1 and −1, respectively. The horizontal axis is the RMS value of the AE signal in the time domain, and the vertical axis is the energy characteristic coefficient extracted through the wavelet analysis. The RMS and energy characteristic coefficient values were normalized to equalize the scales. The left side of the hyperplane is the area representing the “normal” state of the grinding wheel, whereas the right side represents the “worn” state.

3 Experiments

3.1 Equipment and specifications

The BE-WF-502 N NC (Shonan Optics, Japan) centering machine was used as the experimental platform, and the hydrophone-type AE sensor was installed to obtain
AE signals during grinding. AE signals were generated from the stress wave at the cutting point. The stress wave is released by the damage of the material internal structure. It transfers into acoustic wave and is transmitted away through solid or fluid medium. In this study, surface quality of the grinding wheel and the material removal rate of workpiece were the main object to be monitored. To prevent the interference mainly from the machine, the ideal condition was that the sensor only read the acoustic wave at the cutting point except for other interference. A solid-state waveguide was unable to directly connect to the cutting point. It was difficult to set a built-in AE sensor on the centering machine which generated most of the disturbance. A hydro-state waveguide such as the cutting fluid can more completely transmit the acoustic wave to the sensor, since the cutting fluid directly jetted from the sensor to the cutting point. There is only one path, which is to the sensor, for the acoustic wave in the fluid to be transmitted. Moreover, the interference from the disturbance on the machine could be rarely transmitted to the sensor through the nozzle, which was the only solid in contact with the AE sensor. A fluid hydrophone AE sensor was applied, which was connected to the nozzle of the cutting fluid pipe. The cutting fluid flows through the hydrophone and to the cutting point. As a result, the acoustic wave was transmitted through the cutting fluid from the cutting point to the AE sensor.

After preprocessing steps, such as amplification and filtering, the data were transferred to a computer for analysis. Figure 7 presents the experimental setup.

### 3.2 Design of the Taguchi experiment

The Taguchi method of robust design requires relatively few experiments to determine the influence of process factors on workpiece quality [35–37]. This study used the Taguchi method to design a three-factor, three-level experiment. As shown in Table 1, three levels have been considered for each parameter. The experiments were designed using L9 standard orthogonal array as given in Table 2. The effects of the
holder parameters on the quality of the processed lens were evaluated. In Fig. 8, \( \theta \) represents the deviation angle of the optical axis, \( x \) represents the edge thickness difference of the lens in micrometers, and \( d \) represents the holder diameter in millimeters. Factor \( \theta \) was considered one of the control factors, but it is difficult to directly measure. Therefore, the ratio of \( x \) to \( d \), which represents the holder error ratio in Table 1, was used as a control factor instead of \( \theta \). Because the effect of holder material on lens quality is substantial, the Young’s modulus (MPa) of the holder material was selected as a control factor.

According to Eq. (1), feed rate is a factor affecting the MRR, which directly affects the processing time. Consequently, among the working parameters of the centering machine, the feed rate was used as a control factor. Lenses with different specifications require an appropriate rotation speed for the grinding wheel. If the speed is too high, the lens is easily burned by friction heat. Low speed results in cracks on the surface of the lens due to compressive stress. This study selected grinding wheel speed of 2400 rpm, which is suitable for quartz. Other grinding parameters were set as constants. Target diameter was 37.65 mm, grinding wheel diameter was 160 mm, feed was 22 mm, workpiece rotation speed was 1 rpm, and spark-out time was 60 s.

### 3.3 Grinding wheel wear experiment

This study tested an FQT2-459 single-layer electroplated diamond grinding wheel (ALPHA DIAMOND CO.) 300 times. The grinding wheel diameter is 160 mm, and the grain size is #350. The surface qualities of the grinding wheels, which was either “normal” or “worn,” was observed using the Micro-Vu image measuring instrument. The RMS value of the AE signal and the third-layer energy ratio, E3, obtained through the wavelet analysis were recorded as reference values for labeling and classification. The SVM model was trained on 216 experimental data points to classify the hyperplane into “normal” and “worn” grinding wheel states, and the SVM model was tested using 84 data points to evaluate the learning accuracy.

Figure 9a displays the surface of the grinding wheel before the experiments, whereas Fig. 9b shows its surface after the 300 experiments (720,000 rotations). The silver parts in the images are diamond abrasives, the gray part is the metal substrate, and the black parts are the holes where

| Table 1 | Control factors and levels of Taguchi method |
| --- | --- |
| | Holder material | Holder error ratio (μm/mm) | Grinding feed rate (mm/s) |
| Level | | |
| Level 1 | Brass (B) | 0.01 | 0.005 |
| Level 2 | Carbon-steel (CS) | 0.005 | 0.015 |
| Level 3 | Teflon (T) | 0.001 | 0.025 |

| Table 2 | Layout of Taguchi experimental design |
| --- | --- |
| Run no | Holder material | Holder error ratio (μm/mm) | Grinding feed rate (mm/s) |
| --- | --- | --- | --- |
| 1 | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 |
| 3 | 1 | 3 | 3 |
| 4 | 2 | 1 | 2 |
| 5 | 2 | 2 | 3 |
| 6 | 2 | 3 | 1 |
| 7 | 3 | 1 | 3 |
| 8 | 3 | 2 | 1 |
| 9 | 3 | 3 | 2 |
the abrasives fell off. The difference between the images indicates substantial loss of abrasives on the surface of the grinding wheel.

4 Results and discussion

4.1 Material removal and shape reconstruction

Figure 10 displays part of the AE signal divided into separate lens rotation cycles. The four peaks in each cycle correspond to the four corners of the square lens; at these points, the MRR was relatively high. The AE signal was positively correlated with the MRR; that is, the cumulative value of the AE signal was relative to the amount of material removed from the lens. The AE signals at each lens angle during each rotation speed were summed. The cumulative value was used to analyze the amount of material removed and the grinding condition at each angle of the lens. The AE signal was transmitted through the cutting fluid concentrated at the cutting point of the grinding wheel. The AE signals consisted of the signals created through material removal and the basic grinding wheel vibration, which had to be subtracted in the analysis. The feed rate of the grinding wheel, flow rate of the cutting fluid, and distance between the grinding wheel and lens affected the basic level of the signal. The basic level of the AE signal differed in every cycle of the lens rotation because the basic amplitude of the AE signal caused by grinding wheel vibration oscillated rather than remained constant. The basic level was the sum of the minimum value and a correction constant. To obtain the cumulative value along the lens rotation angle, the AE signal was converted into a polar plot in the angular domain. The signals at the same angle were summed.

Because AE signals are positively correlated with the MRR, the ratio between the cumulative values at different angles should be similar to the ratio of the removal length. In this experiment, the lens width and height before centering were 42.20 and 41.30 mm, respectively. The lens diameter after centering was 37.60 mm. In Fig. 11, a–c represent the removal lengths at the corner, upper side, and right side, respectively.

The correction constant and the scale from the AE signal to the removal rate were evaluated on the basis of the length ratio a:b:c, which is ideally 1:0.1725:0.2145. Upon comparison of the processing time with the AE signal, a time difference was identified. As feeding of the grinding wheel began, the lens was rotated for an angular shift. Before the correction constant and scale were evaluated, we compensated with an angular shift of 0.2 rad.

The original shape of the square lens before the process was reconstructed, with an evaluated correction constant of 30.2 V and a scale of 5. Figure 12a presents the original AE signal and the basic level. The length ratio a:b:c was 1:0.1733:0.2155, and the error in the reconstruction was 17.87%. Figure 12b displays the cumulative AE polar plot, fitted shape and ideal shape.
Errors between the ideal shape and fitted shape mainly occurred on the right margin, upper-right margin, and lower-left corner. On the right and upper-right margins, the amount of rebuilt material was greater than the ideal one. This result indicated that the estimated amount of removed material was greater than the ideal amount. At the lower-left corner, the estimated amount of removed material was smaller than the ideal amount. An edge defect was identified on the centered lens (Fig. 13). The defect consisted of a large amount of removed material, corresponding to angles 0–30° in Fig. 12b. The excessive removal at 60° was offset by insufficient removal at 240° (Fig. 12b). The offset maintained the diameter at 60°, which is close to the average diameter, but caused eccentricity at 60°. The variation in the cumulative data indicated that cracks were generated during the process. According to an inspection of the lens after process, the cracks were shorter than 0.1 mm.

In this case shown in Figs. 12 and 13, the eccentricity and edge defect were solved by improving the process parameters. Feed rate was decreased from 0.005 to 0.002 mm/s to prevent the lens eccentricity. Spark-out time was increased to 120 s to insure the circularity and eliminate the edge defect. The lens quality with improved parameters was circularity error of 0.01 mm and crack length of 0.1 mm. The shape reconstruction method is based on the positive correlation between the AE signal and material removal rate. It implies the material removal at each angle, including surface roughness, circularity, cracks, and any other edge defects. Operators can immediately find out the material removal problems and adjust the process parameters.

### 4.2 Wavelet analysis

The energy of mechanical wave is proportional to its amplitude. To quantify the energy of the wavelet band of each level, the energy coefficient of the approximate layer and each detailed layer were calculated by the square of the amplitude. The energy of each detailed layer was divided by the total energy coefficient to obtain the characteristic coefficient, which represents the energy carried by each layer, which was calculated using the following equations:

\[ E = E_A + E_D \]  \hspace{1cm} (5)  

\[ E_A = A^2 \]  \hspace{1cm} (6)  

\[ E_D = \sum_{i=1}^{I} D_i^2, \quad i = 1, 2, \ldots, I \]  \hspace{1cm} (7)  

\[ E_i = \frac{D_i^2}{E}, \quad i = 1, 2, \ldots, I \]  \hspace{1cm} (8)  

where \( E \) is the total energy coefficient of the wavelet, \( I \) is the number of decomposition layers, \( E_A \) is the approximate
layer energy coefficient, \( E_D \) is the detailed layer energy coefficient, \( A \) is the amplitude of approximation layer, and \( D_i \) is the amplitude of each detailed layer.

Figure 14 presents the wavelet energy coefficient distribution obtained from the experiments. B1–B3 refer to the experiments using brass holders, CS1–CS3 refer to the experiments using carbon steel holders, and T1–T3 refer to the experiments using Teflon holders. E7 is the most significant energy ratio. The high E7 values for B1–B3 indicated that the AE signals in the experiments using brass holders contained more low-frequency vibration components, which are considered noise due to mechanical vibration.

4.3 Experiment analysis

This study designed a Taguchi experiment to analyze the influence of each factor on lens quality. Table 3 presents the corresponding L9 orthogonal table.

Table 4 presents the instruments used to measure lens quality.

In the Taguchi method, the signal-to-noise (S/N) ratio is a useful indicator when attempting to improve the robustness of a process and minimize the effect of noise on the output. The parameters can be adjusted to stabilize the process if the S/N ratio is relatively large. Figure 15 presents the S/N ratio of each control factor, where \( E \) is the Young’s modulus of the holder material, \( PV \) is the holder error ratio, and \( FR \) is the grinding wheel feed rate. The outputs of the experiments were the-smaller-the-better because they represented lens defects or mechanical vibration signals.

An analysis of variance (ANOVA) has been done to verify the significance of the controlled factors. The contribution ratio (%) is obtained by dividing the variance of each factor by the sum of all variances. The results are listed in Table 5, showing that holder material was significant to the lens qualities, and holder error ratio causes a little influence on the lens qualities. Grinding wheel feed rate is less significant.

The S/N ratio indicated how the holder material, edge error ratio, and wheel feed rate affected the lens process.
The brass holders were easily deformed because of the low Young’s modulus of brass. The deformed holders decentered the lens and caused external vibration, which was a low-frequency component of the AE signal. Consequently, E7 had the largest wavelet energy coefficient, and the lens circularity was poor. The carbon steel holders could hold the lens stably and decreased the grinding vibration because of carbon steel’s high stiffness and friction coefficient. The optical axis error, edge crack length, and grinding surface roughness were superior to those generated in the tests using brass holders. However, the polished surface was damaged by the holders because of carbon steel’s high stiffness and friction coefficient. The Teflon holders had the smallest Young’s modulus; it barely scratched the lens or derailed the working process. However, because Teflon’s low surface strength caused the holder to be damaged easily, the holder’s lifetime was short. In addition, the extremely low friction of the material meant that if the normal force of the grinding wheel could not be resisted by the holder, the lens would have been pushed away from the working axis.

A holder with an edge error indicates that the contact area between the holder and the lens’ polished surface is uneven. This condition increases the compressive stress between the holder and lens and thus increases the length of scratches on the surface of the lens. However, the compressive stress on the surface of the lens represents the holding force of the holder, and such force stabilizes the grinding process. Therefore, the grinding quality is more stable with a holder edge error of 0.0005 than with a holder edge error of 0.0001. However, an edge error of 0.01 is sufficiently large to strongly affect decentering of the edge surface when the lens is rotated. Therefore, the optimal holder error ratio is between 0.0001 and 0.0005.

In the case of a fixed grinding wheel speed, the lower the feed rate, the less material removed per revolution and the smoother the surface of the ground lens. Because the surface of a sintered diamond grinding wheel is uneven, the vibration it causes is large. However, the larger the feed rate, which is proportional to the depth of cut, the more strongly the vibration signal can be suppressed. Therefore, when the feed rate is 0.015 mm/s, the shortest cracks are obtained. According to the ANOVA results, the feed rate affects the residual errors such as the vibration of

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Fig. 15 S/N ratio of each output (the-smaller-the-better). a Circularity error. b Wavelet energy ratio E7. c Scratch length. d Ground surface roughness. e Crack length. f Optical axis error
the grinding wheel spindle. As a result, the effect of feed rate on the processed lens qualities in this experiment is less significant.

4.4 SVM classification model

Under identical parameters, the amplitude of the AE signal increased with the processing time. The grinding mechanism gradually may have changed from grinding to friction and normal stress because of wear of the grinding abrasives, which destabilizes the process (Fig. 15).

The RMS is a useful indicator for evaluating the wear on a grinding wheel’s abrasives. However, a start-up centering machine works with a relatively high RMS value. The process was halted at experiment numbers 50 and 100 and restarted with an RMS value approximately 20 V higher than the previous value (Fig. 16). The RMS alone is not sufficient to accurately evaluate the degree of wear. Another indicator should be used to improve the accuracy of the evaluation. As discussed in Sect. 2.2, in wavelet analysis, E3 is associated with material removal. Therefore, the E3 coefficient and RMS value of the AE signal were employed to construct the classification data set for the SVM.

The experimental data were separated into two groups. The first 150 experimental data points were marked as indicating a “normal” wheel surface (+1), whereas the last 150 experiment data points were marked as indicating a “worn” surface (−1). The SVM model was trained and tested using the data, with the outliers being filtered out beforehand. The classification accuracy was as follows:

\[
\text{Accuracy} = \left( \frac{\text{correctly predicted data}}{\text{total testing data}} \right) \times 100\%.
\]

Figure 17 presents the results of the linear classification. The SVM model classified wheels into “normal” and “worn” groups with an accuracy of 89% when outliers were included and 95% when they were excluded.

As the grinding wheel became worn, both the RMS and wavelet feature E3 of the AE signal increased. The data points were distributed toward the upper right of the diagram. Consequently, the hyperplane that separated the data points into the “worn” and “normal” states was a line with a negative slope. The margins on both sides of the hyperplane were a certain distance from the hyperplane. The data points between the margins indicated that a normal wheel was going to become worn or that a worn wheel was not completely worn.

With the classification model, the hyperplane could be used to evaluate the surface condition of a grinding wheel and make appropriate decisions. The condition of the grinding wheel can be determined, and the appropriate operational decision can be made by examining the distribution of data collected in real time relative to the hyperplane. Worn grinding wheels can be repaired or replaced before grinding is resumed to ensure the quality of the processed lens.

According to the results of the experiment, a square quartz biplane lens has been processed with optimal centering parameters. The MRR has been monitored, and the lens shape has been reconstructed through data processing. The quality of the surface of the grinding wheel has been controlled by applying the SVM model. With this analysis method, the centering process and additional inspection procedures have been optimized. According to the results of the experiment, the quality of the lens has been improved to an edge surface roughness of $< 2\ \mu\text{m}$, a lens circularity error of $< 0.01\ \text{mm}$, a crack length of $< E\ 0.1$ and an optical axis error of $< 150\ \mu\text{rad}$.
5 Conclusion

This study proposed a method for analyzing the optical quartz lens centering process. The MRR was monitored using a fluid hydrophone AE sensor. The shape of the original square lens was reconstructed using accumulated AE signals obtained in the angular domain of the lens. With a rebuilding error of 17.87%, cracks, eccentricity, and edge defects were verified through comparison with the processed lens.

An L9 Taguchi experiment was designed to analyze the effects of the lens holder’s parameters and the grinding wheel feed rate on lens quality. Wavelet analysis was performed to obtain the energy coefficient for different frequency domains. By combining a Taguchi experiment and wavelet analysis, the process parameters were optimized. A linear SVM classification model was constructed and trained to monitor grinding wheel quality; the model had accuracy of 98.8%.

By using this analysis method, the quality of the workpieces can be controlled to an edge surface roughness of $<2\ \mu m$, a lens circularity error of $<0.01\ \text{mm}$, a crack length of $<E\ 0.1$, and an optical axis error of $<150\ \mu\text{rad}$.

Author contribution Chun-Wei Liu: Conceptualization and Supervision; Shaiu-Cheng Shiu: Quartz lens shape reconstruction, Reviewing, and Editing; Kai-Hung Yu: SVM classification, Experiment Design, and Writing.

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Declarations

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Consent to participate All authors were fully involved in the study and preparation of the manuscript; each of the authors has read and concurs with the content in the final manuscript.

Consent for publication All authors consent to publish the content in the final manuscript.

Conflict of interest The authors declare no competing interests.

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