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Digital Twin-based Optical Glass Lens Centering Machine Rebuilding and Variable Parameter Planning based on Motion Control System

Shiau-Cheng Shiu[1], Ke-Er Tang[1], Chun-Wei Liu[1]

[1] *Department of Power Mechanical Engineering, National Tsing Hua University*

s109033802@m109.nthu.edu.tw

Abstract

This research proposes a sustainable method to effectively rebuild an optical glass lens centering machine with digital twin. Furthermore, variable parameter planning is introduced based on its motion control system. Centering process is to align the geometric and optical axes through wheel grinding to minimize the optical axis error. To develop a centering machine with more flexible processing control, a 20-year-old camshaft centering machine was decomposed and secondarily processed to build a 3-axis servomechanism. Some space interference might be in the mechanical design due to the unknown detailed dimensions of old mechanisms. It would take more time and cost to verify the mechanism and control system. Therefore, digital twin was adopted to verify the mechatronic design of the centering machine. With the precise motor control and short cycle time of Siemens motion control system, wheel speed, lens speed and feed rate can be variable during processing. Optical glass lenses are kind of hard and brittle materials that are sensitive to grinding force. Due to the shape of lens and the mechanism of wheel grinding, the effect of centering parameters on lens quality constantly change during processing. Therefore, the variable parameter planning method was developed to maintain the processing quality in the whole duration.
With the digital twin to virtually verify the mechanism and control program, the time to develop a machine can be reduced to 50% comparing to traditional method. Moreover, the energy and material cost can be saved for 20% and 60%. In centering process, the variable parameter planning method enhanced the process efficiency and quality. According to the experiment, the average centering process time was reduced to 80%, and the quality of optical glass lens was improved to edge crack < E0.1mm, 0.9µm < surface roughness < 1.1µm and circularity < 0.01mm.

Centering machine, optical glass lens, digital twin, variable parameter planning

1. Introduction

Optical glass lenses are critical components of the devices in advanced fields such as medical electronics, semiconductor manufacturing, defense, and aerospace. Among various optical performance metrics, optical axis accuracy is the pivotal specification that affects the functional precision of high-end equipment. This accuracy primarily depends on the centering process capability of the optical glass lens. The centering process aligns the geometrical axis with the optical axis by grinding the lens edge.

Improper parameter settings in the centering grinding process lead to defects such as edge crack, poor surface roughness, and poor circularity at the lens edge. These problems significantly increase the difficulty of centering processes for high-end optical lenses. For high-mix-low-volume lens products, the scrap of a single lens results in additional material costs, waste, and extra processing time.

However, current centering machines are predominantly cam-driven mechanical systems or numerically controlled systems. They rely heavily on repeated trial-and-error methods and the expertise of skilled technicians for high-end lens centering. This approach requires much time to develop processes that minimize waste. The centering processes for high-end optical glass lenses are usually inefficient and costly.

Therefore, an advanced centering machine at lower costs is needed to be developed. This should be accompanied by theoretical and experimental analyses of working parameters to establish optimized processing techniques.

K. R. Patil et al. [1] conducted an L9 orthogonal array experiment using the Taguchi method, selecting parameters such as wheel speed, feed rate, depth of cut, and material hardness in high-speed external cylindrical grinding. L. Li et al. [2] developed a grinding force model for robotic belt grinding based on material removal rate of single abrasive grain, predicting grinding forces and material removal rates according to process parameters. J. Zhang et al. [3] studied the influence of wheel speed and grinding temperature on the critical depth of cut in the grinding of hard and brittle materials and analyzed material fracture mechanisms under various parameter settings. Y. Zhang et al. [4] utilized multi-objective optimization algorithms to optimize milling process parameters for different machining features.

Current studies of grinding process have not developed a fully optimization method to adjust for process variations. In previous studies about centering process, the material removal rate (MRR) monitoring has been developed by shape reconstruction method with acoustic emission sensor [5]. MRR has been proved to be the critical feature for the quality of lens grinding. Moreover, the digital twin-driven system has been built and adopted in the real production line. The system could be used to optimize working parameters of centering process in time[6]. However, for higher level optical glass lenses, a set of fixed working parameters can not perfectly finish the centering process.

Therefore, this research aims to implement a centering process control system for optical glass lenses using variable process parameters. This system enables the centering process to achieve high-precision standards required for advanced optical lenses while promoting green manufacturing practices.

2. Grinding theory of glass lens centering process

To analyze the relationship between process parameters, material removal rate, and grinding quality, this study establishes a mathematical model for material removal rate in the centering process. The lens center is set as the origin, and the entire lens is considered stationary to create a coordinate system. Since the grinding wheel feeds into the lens while the lens rotates, the centering model adopts a polar coordinate system to simplify the representation of the grinding wheel's position.

In the actual centering process, the grinding wheel feeds toward the lens center while the lens rotates. Relative to the stationary lens in the model, the grinding wheel revolves around the lens center. Additionally, due to the grinding wheel's feed motion, the wheel simultaneously approaches the origin during its revolution, resulting in a gradually decreasing radius of revolution, as illustrated in Figure 1.

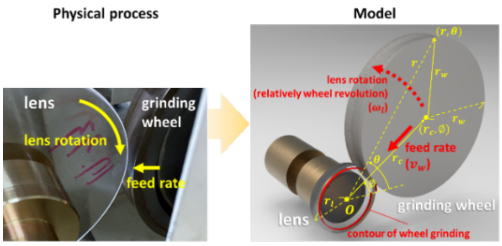

Figure 1. Real centering process and corresponding mathematical model

The mathematical model of centering process is mainly about the geometrical relationship between the lens and the grinding wheel. In the polar coordinate space, the function of a circle is as shown in equation (1):

$$f(r,\theta) = r^2 - 2rr_c\cos(\theta - \emptyset_c) + {r_c}^2 = R^2 \quad (1)$$

where $(r_c, \emptyset_c)$ is the center of circle, (r, θ) is the polar coordinate of any point. R is the radius of circle.

The center of the grinding wheel $(r_{gc}, \emptyset_{gc})$ is shown in equation (2), where R_w is the radius of grinding wheel, R_l is the original radius of lens, f is the feed rate of grinding wheel, ω_l is the rotation speed of lens, t is time.

$$(r_{gc}, \emptyset_{gc}) = ((R_w + R_l - ft), \omega_l t) \quad (2)$$

Refering to equation (1) and (2), in polar coordinate, the location of grinding wheel changing with time is derived in equation (3):

$$r^2 - 2r(R_w + R_l - ft)\cos(\theta - \omega_l t) + (R_w + r_l - ft)^2 = {R_l}^2 \quad (3)$$

Therefore, the material removal rate (MRR) can be derived by calculating the volume of lens covered by the grinding wheel in each moment, as shown in equation (4):

$$MRR = dW\omega_w(R_l + \frac{1}{2}ft) \quad (4)$$

where d is the grinding depth, W is the width of lens at the grinding point.

3. Rebuilding of optical glass lens centering machine

This study develops a motion-control-based centering machine using the framework of an existing cam-driven centering machine as the foundation for an advanced centering system. By replacing the outdated Nakamura OMT-70C high-end centering machine with a newly developed servo-driven machine, this approach saves development time and costs while significantly enhancing machining performance. The centering machine rebuilt in this research was originally a 20-year-old cam-driven centering machine. By reusing the base and castings of the existing equipment, the newly developed green machine minimizes the scrapping costs of old mechanisms, reduces the machining costs of new structures, and shortens the casting processing time. This maximizes the benefits of existing equipment, reduces energy consumption during manufacturing, and lowers carbon emissions. The total weight of reused critical components from the original equipment, which are mainly precise functional parts and castings, is 410 kg, which is 89.13% of the total weight. As a result, equivalently about 806.88 kg of carbon emission was saved by rebuilding this centering machine.

The development of the centering machine in this study is illustrated in Figure 2. The core functionality of the centering machine is centered on customizable process settings, allowing the configuration of movements, feeds, sparkings, and chamfering processes. The machine operates with a basic three-axis configuration comprising the tool axes (X and Z) and the workpiece rotation axis (C). Combined with wheel rotation, air-actuated clamping, and coolant flow control, this minimal set of functional components supports the design of centering processes from simple to complex.

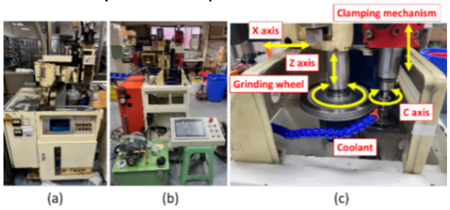

Figure 2. Centering machine (a) before: cam-driven (b) after: servo-driven (c) control elements of developed machine

This study employs a Siemens motion controller and 400W servo motors to establish the control system for the centering machine. Multi-axis synchronized motion control is done in the PLC modular architecture, meeting the machining requirements of the centering process. For communication, the Profinet protocol is used to link the control system, while OPC UA connects the controller with an edge computing computer. This setup facilitates real-time monitoring of the centering process equipment and instant feedback on process parameters.

4. Process verification by digital twin

During the equipment development phase, the digital twin technology was utilized to construct a virtual model of the motion-controlled centering machine. This virtual model was integrated with the electronic control system to perform motion simulations and data synchronization. Through mechatronic integration simulations, the majority of mechanical and control validations could be completed prior to physical equipment assembly. This approach reduces the cost of physical testing and promotes green manufacturing. The digital twin framework is illustrated in Figure 3.

In terms of mechanical design, the original centering machine was operated with a cam-based mechanism. To accommodate the new servo-driven mechanism, all reused castings, except for the base, required secondary machining to adjust their configurations. These adjustments, combined with new components, formed the foundation for the new mechanical design. With the digital twin model, the alignment and spatial interference of the mechanism were verified during the design phase.

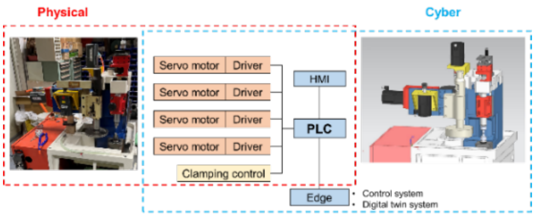

Figure 3. Cyber-physical mapping structure in digital twin system

To develop the centering processing, the virtual machine was employed to test the centering process functionalities. Edge grinding, chamfering, and the operations such as clamping, feeding, and optical alignment can be virtually tested instead of using real machine. Additionally, the virtual model enabled the evaluation of compatible grinding wheel and lens specifications during simulation testing. The spatial feasibility of the centering process was ensured and the abnormalities during actual machining were prevented. The virtual verification of machine spatial design is illustrated in Figure 4.

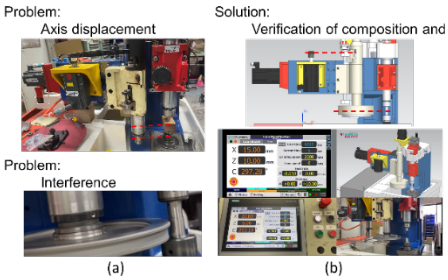

Figure 4. Mechanical verification by virtual machine of digital twin

As for electronic control, the driving system was upgraded from single-stroke cam-driven mechanism to a three-axis servo-driven mechanism. A complete rebuild of the control system is neccessary. The digital twin system was utilized to simulate and rapidly detect defects in the control program.

Since the new machine integrates both existing mechanism and newly designed components, it is challenging to evaluate the load requirements for each motor axis. By employing the electromechanical simulation in the digital twin, the system analyzed the acceleration, momentum, and torque of the machine during operation. This approach enabled the pre-verification of motor capabilities, serving as a critical basis for motor evaluation.

5. Experiment

As shown in Figure 5, in this experiment, the cutting tool is the single-layer electroplated diamond grinding wheel with diameter 150mm and granularity #230. The workpiece is the concave-convex S-NBM51 lens with radiuses of surface curvatures 25mm and -120mm, diameter 24mm, and central thickness 3 mm. The holders are two bell-shaped copper clamps.

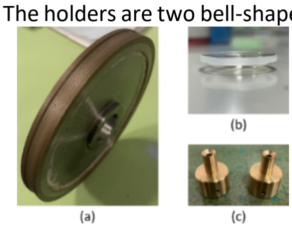

Figure 5. The (a) grinding wheel (b) glass lens (c) clamps for experiment

The centering process with the mentioned grinding wheel, glass lens and clamps in the centering machine rebuilt in this study is shown in Figure 6. A full factorial experimental design with three factors, grinding wheel speed, lens rotation speed, and feed rate, and three levels for each was employed. A total of 27 experimental runs were done, as illustrated in Table 1. The experiment aimed to observe the effects of these process parameters on edge cracks, surface roughness, and circularity of the lens.

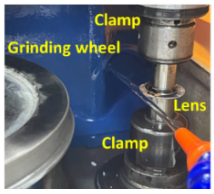

Figure 6. The centering process with the machine rebuilt in this study

Table 1 3-factor-3-level full factorial experiment design

Factor/Level	Low	Middle	High
Grinding wheel speed, ω_g (rpm)	1,500	2,000	2,500
Lens speed, ω_l (rpm)	1.5	2	2.5
Feed rate, f (mm/s)	0.005	0.010	0.015

According to the analysis of the experimental design results, the influence of working parameters on edge crack, ranked from highest to lowest, is f, ω_g, and ω_l. For surface roughness, the ranking is ω_g, ω_l, and f. For roundness, the ranking is ω_g, ω_l, and f. The parameter effects on lens quality are shown in Figure 7. Compared to ω_g and ω_l, the influence of f on surface roughness and circularity is relatively negligible.

According to the main effects plot for lens quality parameters shown in Figure 7, a lower feed rate f results in smaller edge cracks. Higher grinding wheel speeds ω_g improve surface roughness and circularity but expand edge cracks. Increasing lens rotation speed $\boldsymbol{\omega_l}$ helps th grinding stress to be distributed, thereby reducing edge crack depth. However, it significantly worsens surface roughness and circularity, negatively impacting the final quality.

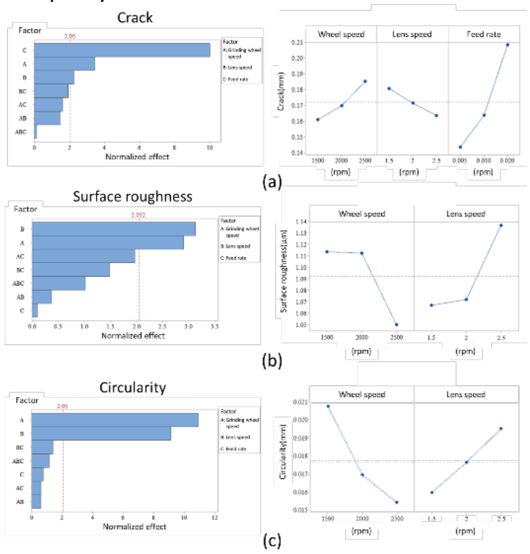

Figure 7. The Pareto charts and main effect of working parameters on lens qualities (a) crack (b) surface roughness (c) circularity

Based on the analysis results derived from the experimental design, the centering process should adapt the grinding parameters as the grinding depth changes, particularly from the initial wheel-to-lens contact phase to the fine grinding stage for achieving the target outer diameter. This adaptive approach ensures the highest precision achieved in the shortest possible time.

5. Variable parameter planning and verification results

Based on the influence of parameters on lens quality, the motion control system was utilized to dynamically adjust process parameters such as grinding wheel speed, lens rotation speed, and feed rate according to machining time and processing stage. Compared to conventional methods with fixed parameters, this study employs edge computing integrated with the motion control system to implement a variable-parameter centering process. The variable parameter settings in the centering process is as illustrated in Figure 8.

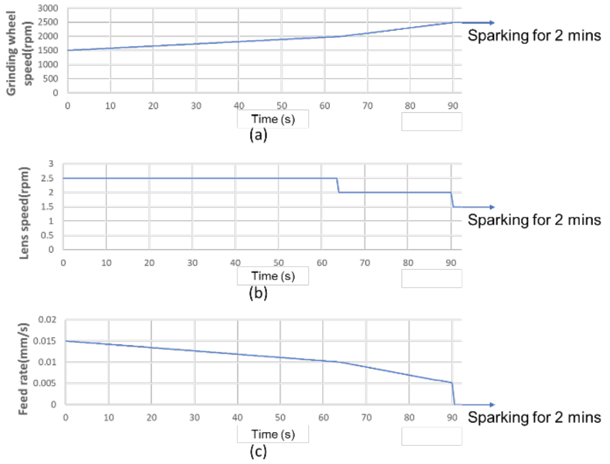

Figure 8. Variable parameter planning of centering process (a) Grinding wheel speed (b) Lens speed (c) Feed rate

In the final verification, totally 25 lenses were processed by the centering machine developed in the research. With the programmed working parameters, the qualities of optical glass lenses were significantly enhanced, as illustrated in Figure 9. Only 2 lenses were scraped. One of them is scraped due to the surface roughness, and the other is due to the circularity.

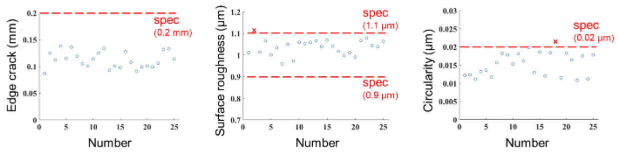

Figure 9. Mass production of 25 lenses in the final verification with programmed working parameters

Finally, the bebefits for development of green machine tool and for variable parameter planning are cummarized in Table 2.

Table 2 Benefits for development of green machine tool with digital twin and variable parameter planning

	This research	Traditional	Improvement
Mechanism used	50 kg	460kg	89.13%
Development time	18 months	24 months	25.00%
Real testing time	10 times	30 times	66.67%
Process development time	2hrs	4hrs	50.00%
Lens scraped by process development	3 pieces	10 pieces	70.00%
Machine needed	1 machine	2 machines	50.00%
Processing time for single lens	180s	240s	25.00%
Lenses completed	23 pieces	20 pieces	15.00%
Lenses scraped	2 pieces	5 pieces	60.00%
Yield rate	92%	80%	15.00%

6. Conclusion

This study rebuilt an advanced centering machine for high-end optical glass lenses based on digital twin, and developed variable parameter planning method based on motion control system.

With the recycle of 20-year-old cam-driven high-end centering machine, a green servo-controlled centering machine for optical glass lens centering was successfully developed. 410 kg of critical components, which is 89.13% of the total weight and is equivalent to 806.88 kg carbon emissions, were saved. The idea of grean machine tool significantly reduced mechanism costs and eliminating the expense of disposing of the old machine.

The digital twin sytem was developed to verify the mechanism, electronic control and the working process. The time for machine development was reduced for 25%. For working process development, the time could be saved for 50%, and the lens used was decreased for 70%.

Based on the grinding theory of centering process and the motion control system, the variable parameter planning method was realized and verified enhancing centering process precision and efficiency. According to the final verification in the centering machine developed by this study, under the specification of edge crack < E0.1, 0.9μm < Sa < 1.1μm, circularity < 0.02mm, the centering process in mass production can be improved that average processing time reduces 25%, scrap rate reduces 60% and yield rate increases from 80% to 92%.

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