In-process Truing of Metal-bonded Diamond Wheels for Electrolytic In-process Dressing (ELID) Grinding

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Electrolytic in-process dressing (ELID) grinding is a new technique for achieving a nanoscale surface finish on hard and brittle materials such as optical glass and ceramics. This process applies an electrochemical dressing on the metal-bonded diamond wheels to ensure constant protrusion of sharp cutting grits throughout the grinding cycle. In conventional ELID grinding, a constant source of pulsed DC power is supplied to the ELID cell, but a feedback mechanism is necessary to control the dressing power and obtain better performance. In this study, we propose a new closed-loop wheel dressing technique for grinding wheel truing that addresses the efficient correction of eccentric wheel rotation and the nonuniformity in the grinding wheel profile. The technique relies on an iterative control algorithm for the ELID power supply. An inductive sensor is used to measure the wheel profile based on the gap between the sensor head and wheel edge, and this is used as the feedback signal to control the pulse width of the power supply. We discuss the detailed mathematical design of the control algorithm and provide simulation results that were confirmed experimentally.

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NOMENCLATURE

Ip = peak current flowing through the ELID cell
K1 = constant for the electrochemical reaction
s_i = corrected distance between the wheel and electrode at different times
S1, S2, S3, S4 = average distance between the wheel and electrode for different wheel segments
T = time for one wheel rotation
t = time
u = pulse duty cycle

1. Introduction

Ultra-precision grinding to achieve a nanoscale surface finish has considerable advantages over other conventional finishing processes such as lapping and polishing.[1] Therefore grinding with metal bonded diamond wheel has become a predominant method for direct machining of ultra-precision optical parts and dies for injection molding parts to replace the expensive and time consuming finishing process like polishing.[2-3] In-process dressing and truing of the grinding wheels are necessary to maintain the accuracy of the finished products. Several ways can be used to do this, including mechanical contact methods (diamond dresser), electrothermal methods (electrical discharge machining), laser technology, and electrochemical techniques. Electrochemical dressing is one of the best methods because of the system simplicity, low noise level, and less damage to the grinding wheel. Electrolytic in-process dressing (ELID) is one of the electrochemical methods for in-process dressing of grinding wheels. This technique uses a metal bonded grinding wheel that is dressed by an electrolytic process during grinding to ensure continuous protrusion of the abrasives from the grinding wheel to achieve a stable finish by grinding with superfine grit.[4] The concept was pioneered by Ohmori and Nakagawa,[5] and the process has been found to be very effective on hard and brittle materials such as ceramics, optical glass, and hardened steel.[6-11]

Uniform contact between the workpiece and the grinding wheel is critical in precision grinding as it plays a major role in the surface roughness and form accuracy of the finished product. Conventional ELID grinding does not ensure controlled and uniform dressing of the grinding wheel to maintain uniform contact with the workpiece. Moreover, spindle runout cannot be mitigated using regular ELID grinding.[6-11] Some work on closed-loop control for stabilizing the ELID current was conducted by Lee[12] but the approach is not appropriate for truing of the grinding wheel. Note that truing is the dressing of the grinding wheel to maintain the uniformity. The work performed by Ashizuka et al.[13] contributes greatly to the truing control of the grinding wheel, but ignores the concept of convolution, which is discussed in Section 3.1. To address these drawbacks, we proposed a methodology to control ELID power by measuring the circumferential profile of the grinding wheel while considering the convolution between the wheel and the electrode to ensure concentric wheel rotation. In our setup, an inductive displacement sensor is used to measure the metal-bonded grinding wheel profile; however other method of profile measurement such as air bearing stylus is also available.[14] These wheel profile data are fed back to the controller to adjust the pulse duty cycle of the ELID power supply. In this paper, we discuss the theory and the simulation of this new concept as well as the experimental implementation in detail.

2. Experimental Setup

The detailed experimental setup is shown in Fig 1. In order to carry out the current research authors have developed intelligent ELID grinding machine with several sensory system.[15] In this study, the grinding wheel profile was monitored in-process using an inductive sensor. This profile data were used to simulate the control algorithm. An optical sensor was applied so that the wheel profile could be measured from the same starting point during each revolution. A Cygnal 8051 development board was used for capturing the wheel profile as well as for generating the desired pulse duty cycle for the ELID power supply. We also developed a user interface to capture and display the profile data in real time.

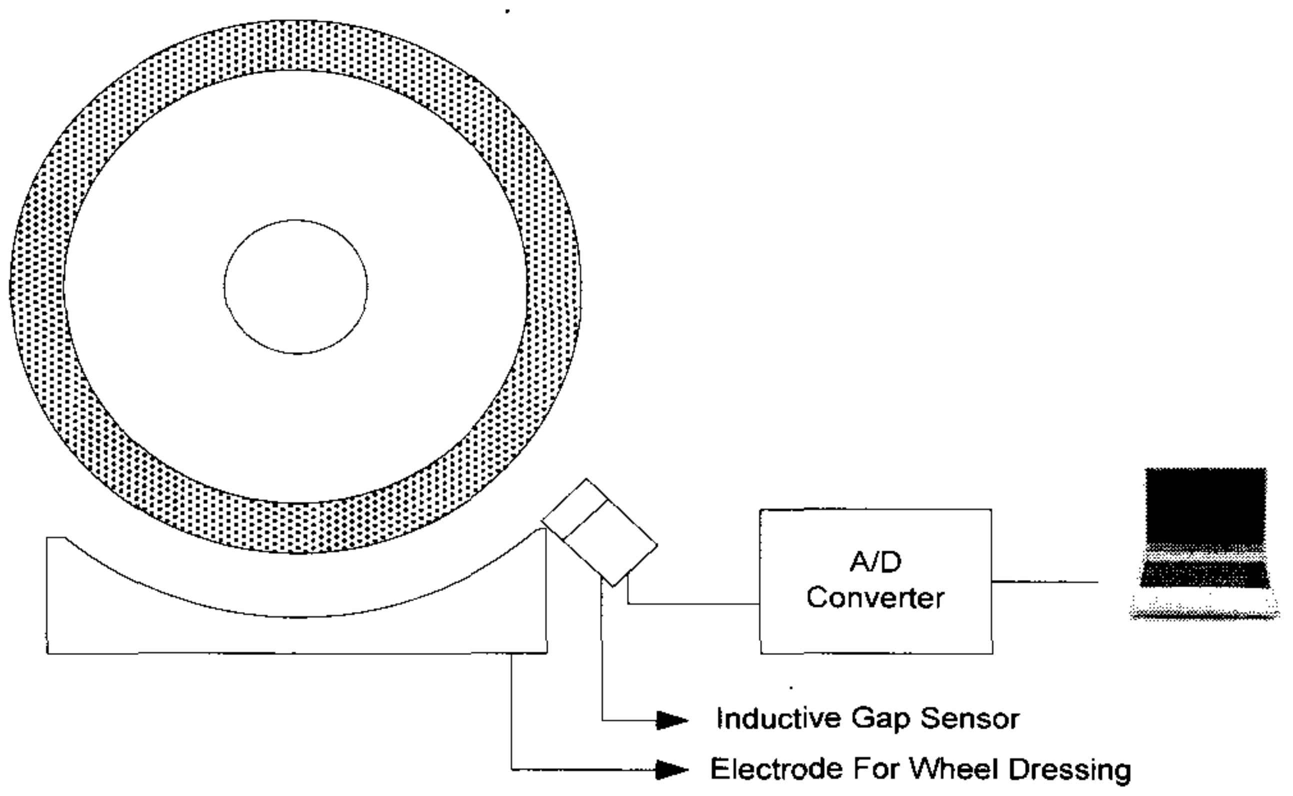

Fig. 1 Experimental setup for wheel profile monitoring

We discuss the mathematical modeling, the simulation, and the experimental implementation of the proposed concept in subsequent sections.

3. Mathematical Modeling

We developed a model of the ELID grinding system and simulated it to develop the closed-loop truing control. This model includes the concept of convolution between the grinding wheel peripheral area and the electrode.

3.1 Convolution

In ELID grinding, the electrode usually covers one-quarter of the perimeter of the grinding wheel, although the sensor head area is much smaller than that. In the previous method of truing control[13], the distance between the sensor head and various points on the wheel surface were measured for one revolution, and then control was applied during the next revolution by varying the pulse width of the power according to the distances measured. This required that the profile data be divided into eight different segments, and the power pulse width changed on a segment level. One major drawback of this approach is that it did not consider overlapping segments. In this paper, we divide the raw wheel profile into four segments before applying the concept of convolution to derive the corrected average wheel profile. Figure 2 shows an example of the true profile data of one wheel revolution divided into four segments, denoted as AB, BC, CD, and DA. The average distance between these segments and the stationary electrode are given respectively by S1, S2, S3, and S4. From the figure, we can see that during one revolution of the wheel, moments will occur when two successive segments come together in the dressing zone; thus, the effective average distance between the wheel and electrode will be different.

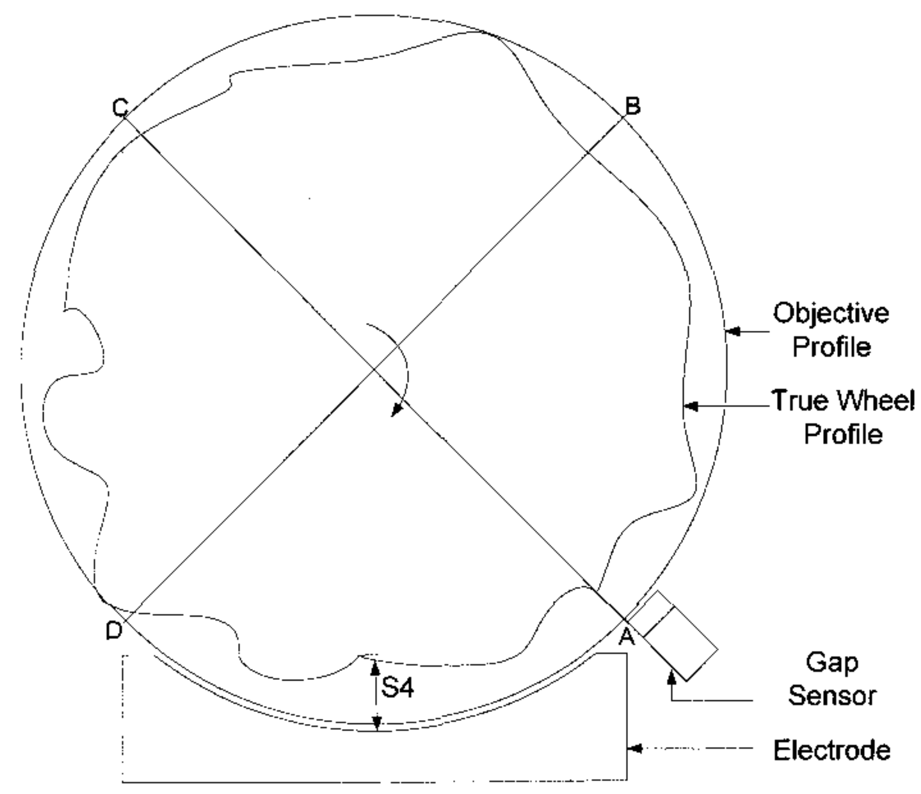

Fig. 2 Convolution concept and overlapping of the segments

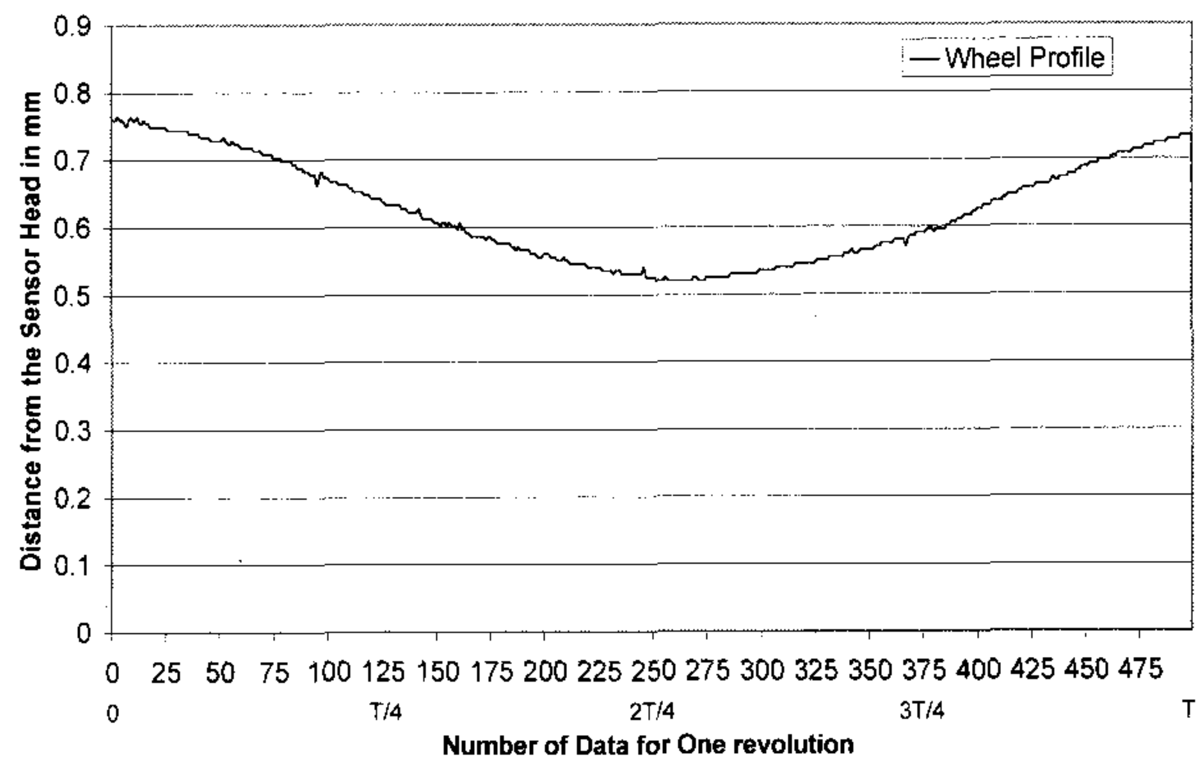

Fig. 3 Raw wheel profile as measured by the inductive gap sensor

Figure 3 above shows the raw wheel profile as measured by the gap sensor. We measured 500 data points per revolution to generate the raw profile. Therefore, the average distance between the wheel and electrode for S1–S4 represents the average of 125 data points. If time taken for one wheel revolution is T, then at different times t, the corrected average distance s_i between the wheel and the electrode is governed by the following equations:

$s_i = S4(1 - 4t/T) + (4t/T)S1$ for $0 < t < T/4$
$s_i = S1(2 - 4t/T) + (4t/T - 1)S2$ for $T/4 < t < 2T/4$
$s_i = S2(3 - 4t/T) + (4t/T - 2)S3$ for $2T/4 < t < 3T/4$
$s_i = S3(4 - 4t/T) + (4t/T - 3)S4$ for $3T/4 < t < 4T/4$

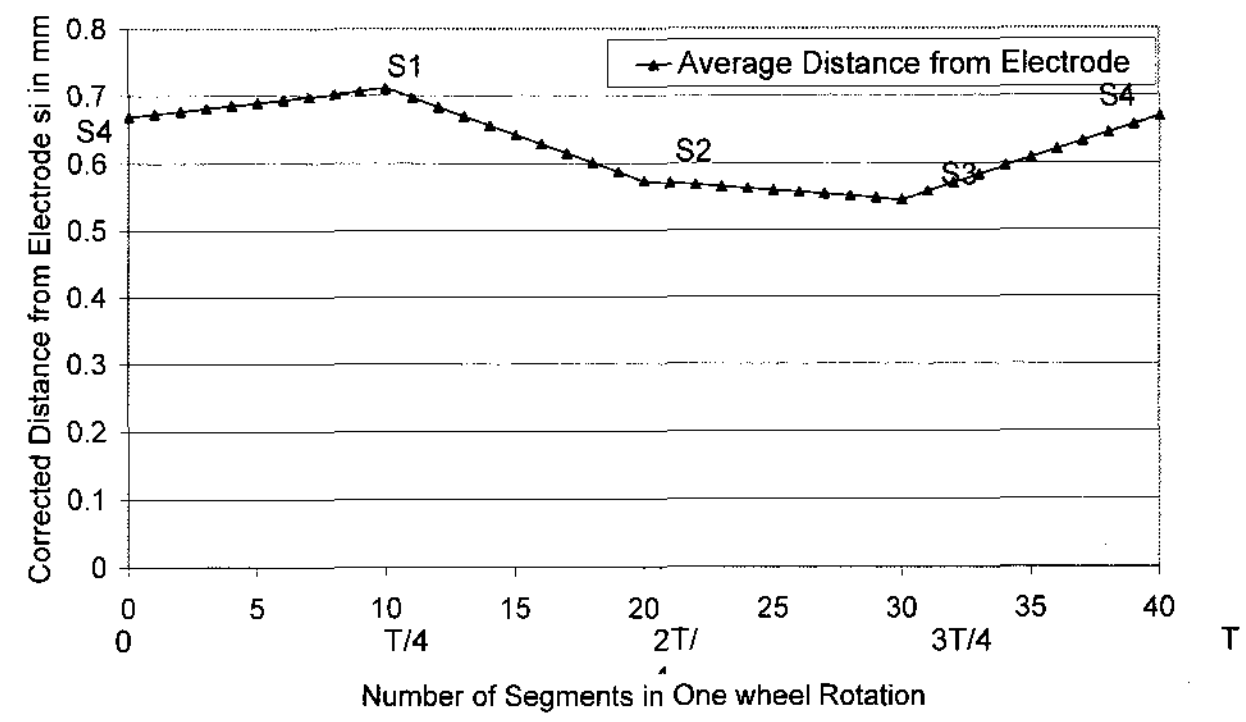

Fig. 4 Wheel/electrode distance after applying convolution

These equations are derived from the convolution theorem, something that was not considered in the previous study.[13] The control signal required to achieve the objective profile of the wheel must be generated based on this measurement. Therefore, calculating the average distance between the wheel and the electrode correctly is crucial. In this paper, the time interval t has been taken as $0.025T$, which implies that s_i will have values from $i = 1$ to 40. Figure 4 shows the values of s_i.
The feedback controller can be designed and implemented after calculating all of the corrected distances.

3.2 Feedback Controller Design and implementation for Truing Control

Designing of the controller

The objective of truing control is to minimize the nonuniform wheel and workpiece contact, which may occur due to the nonuniformity of the wheel or spindle runout. The wheel profile data after correction using the convolution theorem have been used as feedback signals to achieve this goal.
Faraday's basic law of electrochemistry can be applied to derive the model of this system. Mathematically it can be written as follows:

$$ds_i = -K1*Ip*u\ dt$$

In the s domain, $s_i(s)/U(s) = -1/s$. For the sake of simplicity, we assume that the constant $K1*Ip = 1$. We considered the following in the design of the closed-loop controller:

1. Control signals should be applied for the different segments of the wheel, where each segment represents the average distance of the wheel from the electrode.
2. The control signal should be held constant for each segment; therefore, a zero-order hold exists in the closed-loop system.
3. The control objective should be achieved after several iterations, i.e., after several revolutions of the wheel.
4. The reference input to the controller should be different for each iteration.

Using these criteria, we designed a P-controller and restricted the number of segments to 40.

Implementation of the Controller

We implemented the feedback controller for truing control in ELID grinding as shown in Fig. 5.

4. Results and Discussion

We produced some arbitrary data to test the control algorithm we had developed, and the results of the simulation are shown in Fig. 6. This figure clearly shows that the overall nonuniformity in the wheel profile has become very small after the 4th iteration, a maximum of 0.15 mm. The proposed control system will be very effective for truing the wheel in ELID grinding, but the number of iterations required in practice may vary from that in the simulation because the simulation assumed that the delay associated with the microprocessor calculation was zero.
We carried out a pilot experiment with a 1000-rpm spindle speed to test the control algorithm, and the results are shown in Fig. 7.
Figure 7 shows that the wheel profile was more uniform after applying truing control. The improvement in the wheel eccentricity is summarized in Table 1.

The experimental results show that an improvement of 100 microns occurred in the wheel eccentricity, which can be considered a significant achievement. However, the eccentricity was not reduced completely to zero because of the following:

1. The ELID power source did not have enough capacity to generate sufficient current for the electrochemical reaction.
2. The electrolyte may have lost its properties to facilitate the reaction.

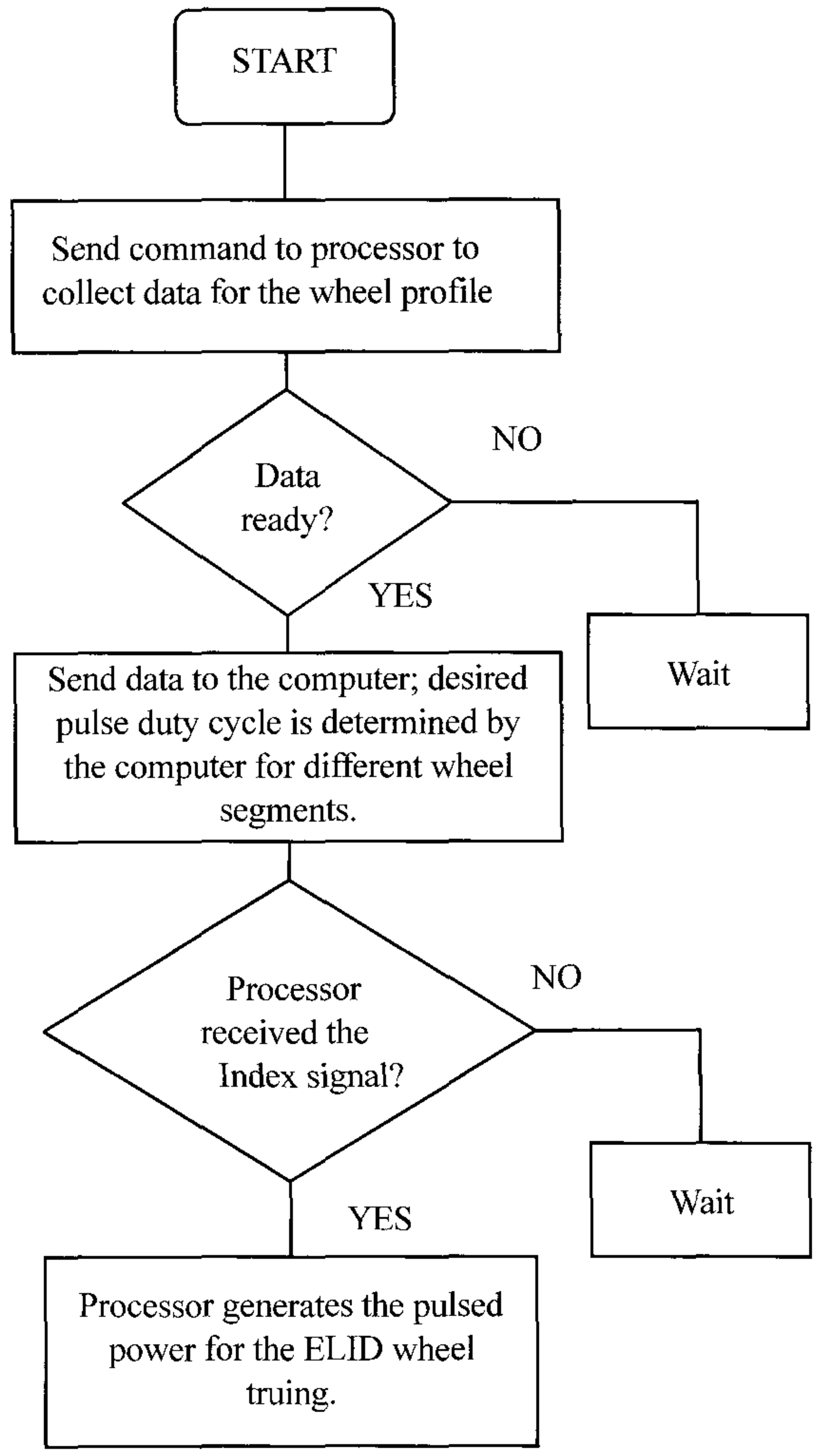

Fig. 5 Flowchart for wheel truing in ELID grinding

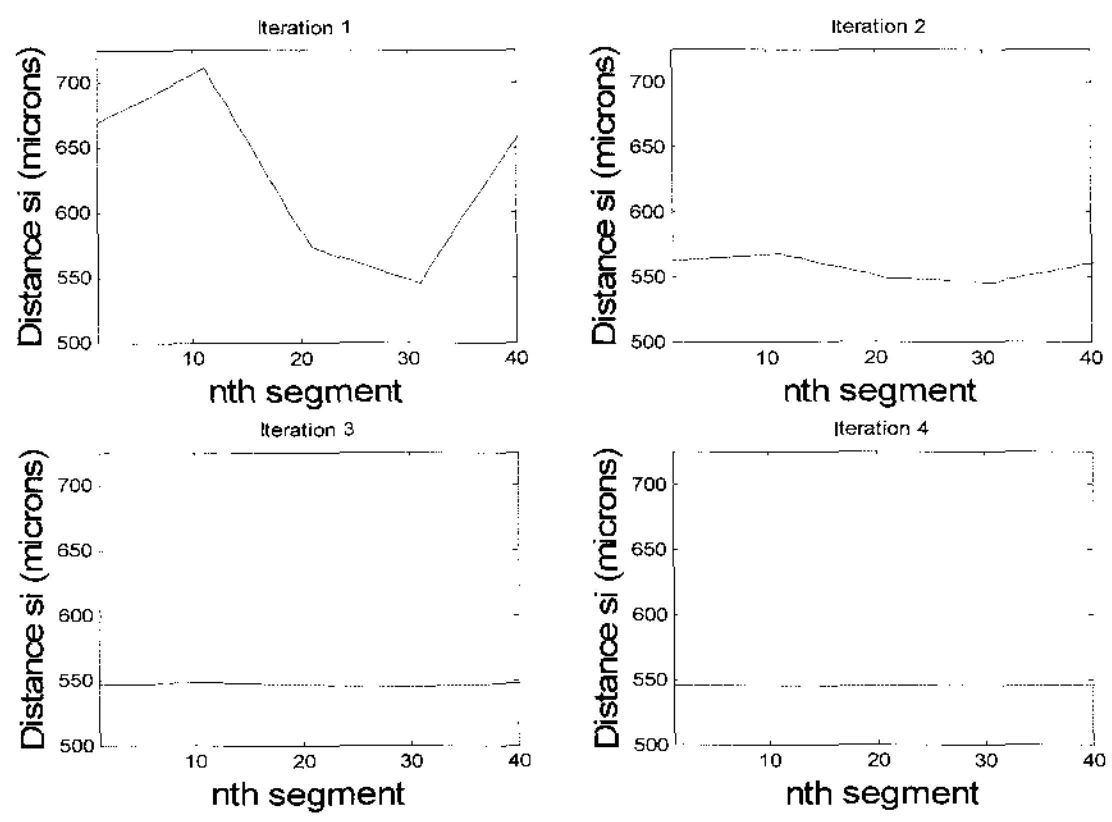

Fig. 6 Simulation result of the proposed control algorithm

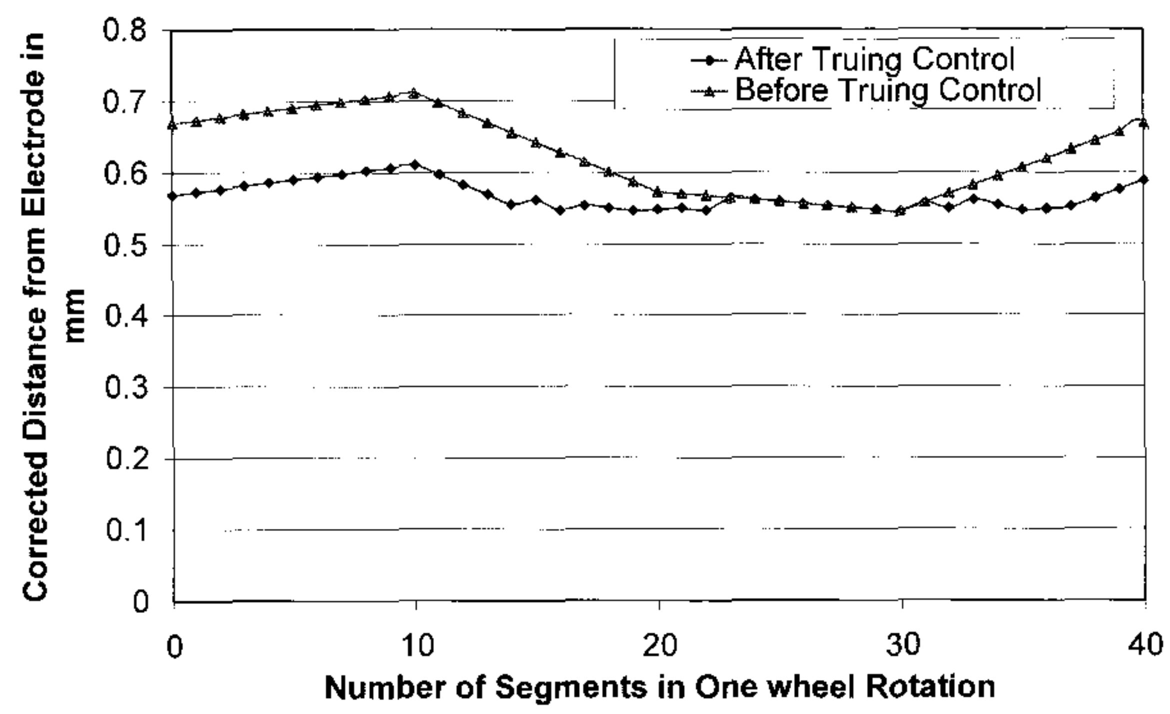

Fig. 7 Average wheel profile before and after implementing truing control

Table 1 Improvement in wheel truing after implementing the control algorithm

	Eccentricity of the wheel [μm]	Improvement [μm]
Without in-process truing	160	100
With in-process truing	60	

5. Conclusions

We designed a control system for truing the grinding wheel in ELID grinding. These are our findings:

1. The concept of convolution was proposed for the feedback signal to overcome the drawbacks of the previous system.
2. A detailed control system was designed and simulated for truing control in ELID grinding. The simulation results were very promising.
3. The developed algorithm was implemented experimentally and achieved a significant reduction in wheel eccentricity.

REFERENCES

1. Rahman, M., Lim, H. S., Neo, K. S., Senthil, K. A., Wong, Y. S. and Li, X. P., "Tool-based nanofinishing and micromachining," Journal of Materials Processing Technology, Vol. 185, Issues 1-3, pp. 2-16, 2006.

2. Lee, S. K., Miyamoto, Y., Kuriyagawa, T. and Syoji, K., "Minimization of Hydrodynamic Pressure Effect on the Ultraprecision Mirror Grinding," International Journal of Precision Engineering and Manufacturing, Vol. 6, No. 1, pp. 59-64, 2005.

3. Isobe, H., Hara, K., Kyusojin, A., Okada, M. and Yoshihara, H., "Ultrasonically Assisted Grinding for Mirror Surface Finishing of Dies with Electroplated Diamond Tools," International Journal of Precision Engineering and Manufacturing, Vol. 8, No. 2, pp.38-43, 2007.

4. Lim, H. S., Fathima, K., Senthil, K. A. and Rahman, M., "A fundamental study on the mechanism of electrolytic in-process dressing (ELID) grinding," International Journal of Machine Tools & Manufacture, Vol. 42, No. 8, pp. 935-943, 2002.

5. Ohmori, H. and Nakagawa, T. "Mirror surface grinding of silicon wafer with electrolytic in-process dressing," Annals of the CIRP, Vol. 39, No. 1, pp. 329-332, 1990.

6. Bandyopadhyay, B. P., Ohmori, H. and Takahashi, I., "Efficient and stable grinding of ceramics by electrolytic in-process dressing (ELID)," Journal of Materials Processing Technology, Vol. 66, No. 1, pp. 18-24, 1997.

7. Ohmori, H., Takahashi, I. and Bandyopadhyay, B. P., "Ultra-precision grinding of structural ceramics by electrolytic in-process dressing (ELID) grinding," Journal of Materials Processing Technology, Vol. 57, No. 3-4, pp. 272-277, 1996.

8. Katahira, K., Ohmori, H., Uehara, Y. and Azuma, M., "ELID grinding characteristics and surface modifying effects of aluminum nitride (AlN) ceramics," International Journal of Machine Tools and Manufacture, Vol. 45, No. 7-8, pp. 891-896, 2005.

9. Ohmori, H., Lin, W., Moriyasu, S. and Yamagata, Y., "Microspherical lens fabrication by cup grinding wheels applying ELID grinding," RIKEN Review, No. 34, pp. 3-5, 2001.

10. Islam, M. M., Senthil K. A., Balakumar, S., Lim, H. S. and Rahman, M., "Performance evaluation of a newly developed electrolytic system for stable thinning of silicon wafers," Thin Solid Films, Vol. 504, No. 1-2, pp. 15-19, 2006.

11. Qian, J., Li, W. and Ohmori, H., "Cylindrical grinding of bearing steel with electrolytic in-process dressing," Precision Engineering, Vol. 24, No. 2, pp. 153-159, 2000.

12. Lee, E. S., "A study on the mirror-like grinding of die steel with optimum in-process electrolytic dressing," Journal of Material Processing Technology, Vol. 100, No. 2, pp. 200-208, 2000.

13. Ashizuka, M., Lim, H. S., Kumar, A. S., Rahman, M. and Khan, M. I., "In-process truing of metal-bonded grinding wheels by pulse width control in ELID grinding," In the proceedings of 3rd International Conference on Leading Edge Manufacturing in the 21st Century, pp. 19-22, 2005.

14. Shibuya, A., Gao, W., Yoshikawa, Y, Ju, B. F. and Kiyono, S., "Profile Measurements of Micro-aspheric Surfaces Using an Air-bearing Stylus with a Microprobe," International Journal of Precision Engineering and Manufacturing, Vol. 8, No. 2, pp. 26-31, 2007.

15. Saleh, T., Rahman, M. S., Lim, H. S. and Rahman, M., "Development and performance evaluation of an ultraprecision ELID grinding machine," Journal of Material Processing Technology, Vol. 192-193, No. 1, pp. 287-291, 2007.