

Computer Control and Process Monitoring of Electrolytic In-Process Dressing of Metal Bond Fine Diamond Wheels for NIF Optics

Rich Boland
ZYGO Corporation
Laurel Brook Rd.
Middlefield, CT 06455

ABSTRACT

Deterministic grinding of large optical components (2600 – 3700 cm² area) using Electrolytic In-Process Dressing (ELID) requires strict process controls for several process parameters. In this paper we describe how the voltage and current characteristics of the ELID circuit may be used to establish viable, in-situ feedback monitoring of the grinding process. The specific approach used was to keep the ELID power supply in constant voltage mode and maintain an average power level that was optimized for each material. This was accomplished by monitoring the pulsed waveform and its frequency spectrum. By controlling the down feed rate it is possible to control the electrical characteristics of the wheel. A control loop was developed to over-ride the feed rate based upon the characteristics of the pulsed waveform. A second ELID process monitor was incorporated into the optic support scheme. To insure the part being ground was in a mechanically stable environment the optic was instrumented with eddy current gauges to detect motion during machining. Based on the data obtained from these sensors the support for the optic was optimized to minimize rigid body motion as well as bending. It has been found that creating a stable platform for machining as well as maintaining control of the ELID system is essential for a deterministic process.

Keywords: Deterministic Grinding, Electrolytic In-Process Dressing (ELID), In-Situ Feedback Monitoring.

1.0 Introduction

Typical optical manufacturing requires several process steps to bring a raw piece of material to its final desired configuration. Process for rough shaping uses fixed abrasive wheels for rapid removal of large volumes of glass. Processes for preparing surfaces for polishing use loose abrasive grinding. A succession of grit sizes is used in a control grind sequence to remove sub-surface damage. For the National Ignition Facility (NIF) a large quantity of optical components are required in a short period of time requiring production rates of several optics per day. To reduce optical manufacturing time, more deterministic and cost effective fabrication techniques would need to be employed. For fine grinding a way to reduce machine time and costs is to replace loose abrasive grinding with a fixed abrasive process. Electrolytic In-Process Dressing (ELID) of fine diamond wheels can be used effectively to eliminate loose abrasive grinding.

1.1 Background

The ELID process has been used for a variety of materials in optical manufacturing^{1,2,3,4}. The ELID technique utilizes electrolysis to perform continuous dressing of fixed abrasive wheels. The machine is configured so the wheel is the positive electrode and placed a certain distance from the cutting face of the wheel is the negative electrode. By having a conductive coolant fill the gap between the cutting face of the wheel and the negative electrode an electric circuit can be made. By applying current to this circuit an anodic and cathodic reaction occurs at the wheel and the electrode respectively. This reaction causes the metal bond wheel to oxidize creating a weak film. The creation of this oxidize layer will allow diamonds to be exposed or oxide layer to be removed so sharp diamonds can be continually cutting. The type of current used has ranged from AC, DC to pulsed DC voltages⁵, this paper describes the use of a pulsed DC voltage.

When machining begins and the oxidation layer begins to grow the voltage and current will show a time dependant evolution. There are several models for this evolution; they describe a decrease in current and an increase in voltage during the grinding cycle⁶. During this increase in voltage the current should reach an asymptotic level indicating the final

resistance of the wheel. The change in the resistance of the wheel is directly related to the amount of oxidation on the wheel. Faraday's Law for electrolysis has been used to develop an expression for the oxidation rate of the wheel⁷. The oxidation

$$\frac{d\xi}{dt} = \frac{\eta M V G_c A_c}{z F g \rho_m A_w}$$

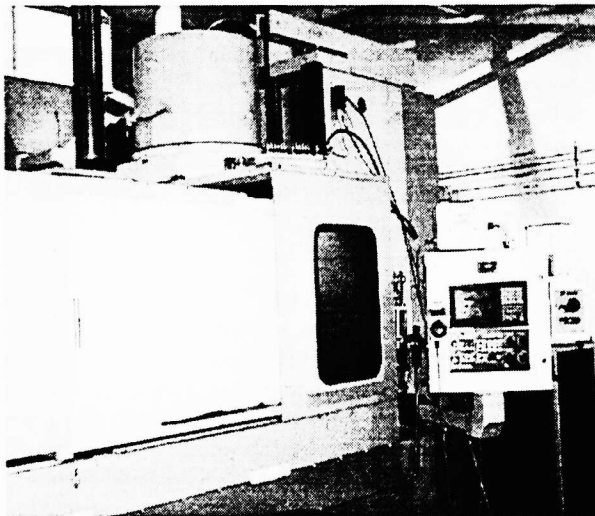
thickness is ξ , η is the cell efficiency factor (which will vary depending on the machine configuration), M is the molecular weight of the wheel, V is the voltage, G_c is the conductivity of the electrolyte, A_c is the active cathode area, z is the valence for the anode, F is Faraday's constant, g is the gap between the wheel and the electrode, ρ_m is the mass density of the anode and A_w is the surface area of the anode being oxidized. By understanding the oxidation rate of the wheel and how it relates to the machining rate can allow the ELID process to be very deterministic. However, when this technique was scaled up to be used on larger optics and wheel sizes the ELID performance can become unstable. To keep the oxidation of the wheel and the electrical characteristics of the circuit in balance, process monitoring was required.

2.0 System Description

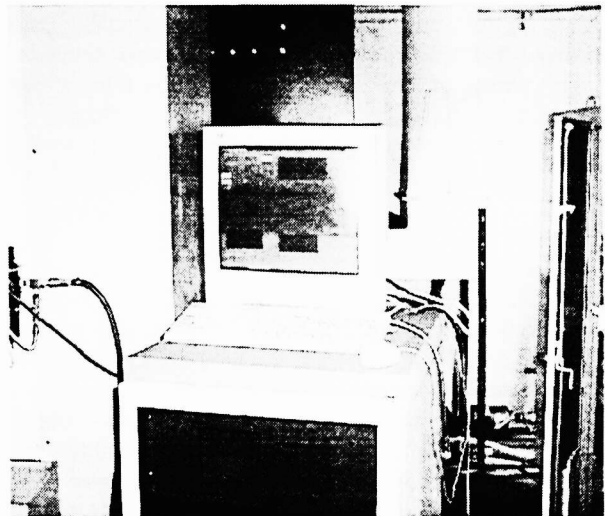
The machine platform for this ELID system is a Toshiba grinding machine (figure 1). The machine was rebuilt and configured with a CNC control, 1000grit grinding wheel and a high voltage pulsed DC supply. The wheel is connected to a variable speed 100 Hp control with a speed range of 200 to 600 RPM.

Grinding Machine	60" Surface Grinder with GE FANUC Controller
Grinding Wheel	36" Diameter Bronze Wheel
Power Supply	200 volt 50 amp DC supply 200 volt 50 amp DC Pulse Generator
Personal Computer	GPIB Interface and Data Acquisition Card

The power supply is custom design, it is a Power Ten high voltage supply connected to a Directed Energy high voltage pulsed generator. The output of the DC supply is interfaced with a PC to monitor the voltage and current fluctuations during machining. The pulse generator output is monitored with an oscilloscope that is interfaced to the PC to monitor the waveform dynamics. The CNC controller has been retrofitted with an interface module for communication with the PC. An application runs along with the machine to monitor the ELID system (figure 2). The operator has the machine voltage, current, wheel load and waveform information displayed real time.



(Figure 1. Toshiba 60" Grinder)

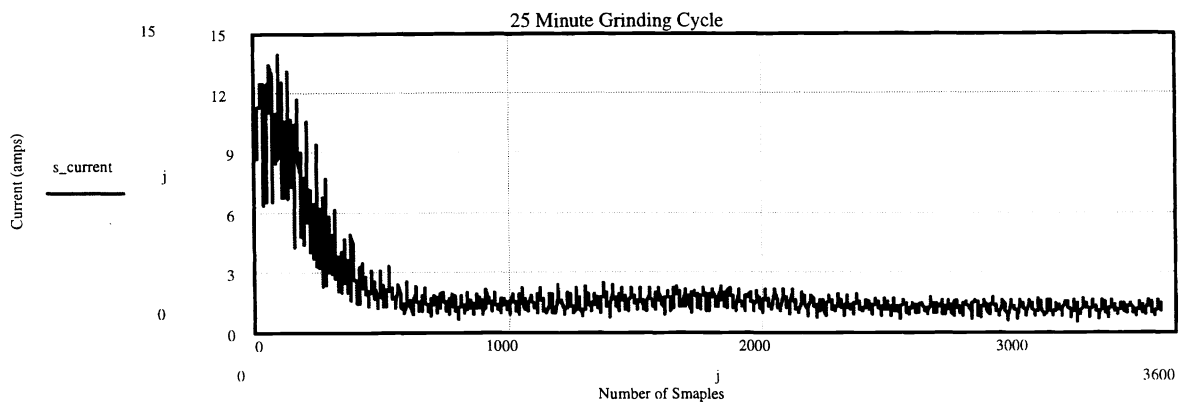


(Figure 2. ELID electronics and Computer system)

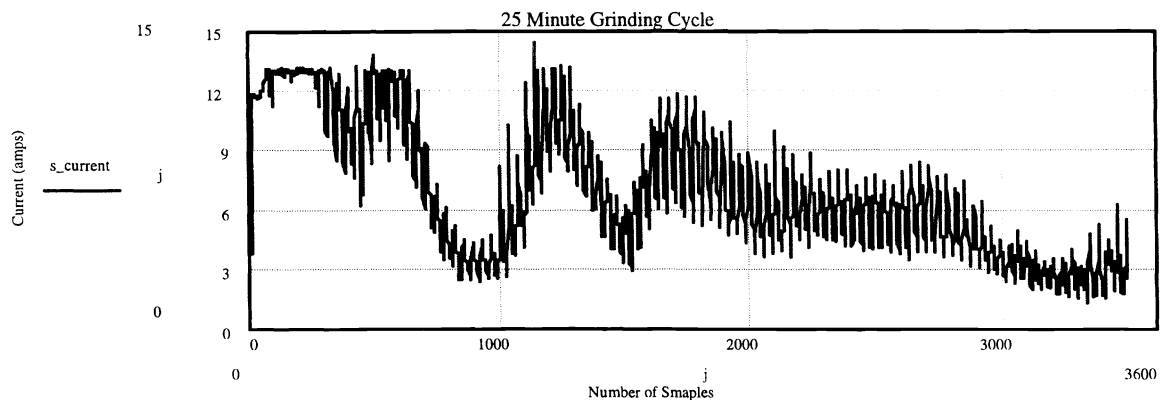
2.1 ELID Process and Controls

The ELID dressing cycle for bronze bond wheels goes through several stages. The wheel starts out in a non-dressed state with the base metal and diamond matrix exposed. After a current is applied across the anode and cathode the outer layer of the metal bond begins to oxidize. As machining progresses the diamonds wear and wheel loads increase causing the weaker oxidized layer to break down exposing new diamond. This change in oxidation layer or insulating layer is a repetitive process continually exposing new diamond for enhanced machining with the finer grit sizes. It has been shown that for bronze bond wheels oxidation actually will grow into and out of the wheel^{7,8}. This effect leads to the need to understand this oxidation/etching of the wheel to have a stable cutting surface. If the oxidation rate is such that it causes this weaker layer to build up during machining it will break down allowing a large portion of the wheel to break down. When the wheel breaks down loose diamond and bond will contaminate the cutting area causing scratching and an increase in sub-surface damage.

As mentioned above the current and voltage have a time dependant evolution that follows an exponential varying function⁹. Based on Faraday's law and the determination of the oxidation rate; if one calculates the total integrated current or charge of the ELID cycle the wheel thickness change can be determined. It has been noticed for this machine and dressing system that the total charge of the system can be correlated to surface quality. Figure three and four show two current records for a grinding cycle using ELID machining an amplifier slab. In figure three the typical exponential decay of the current is



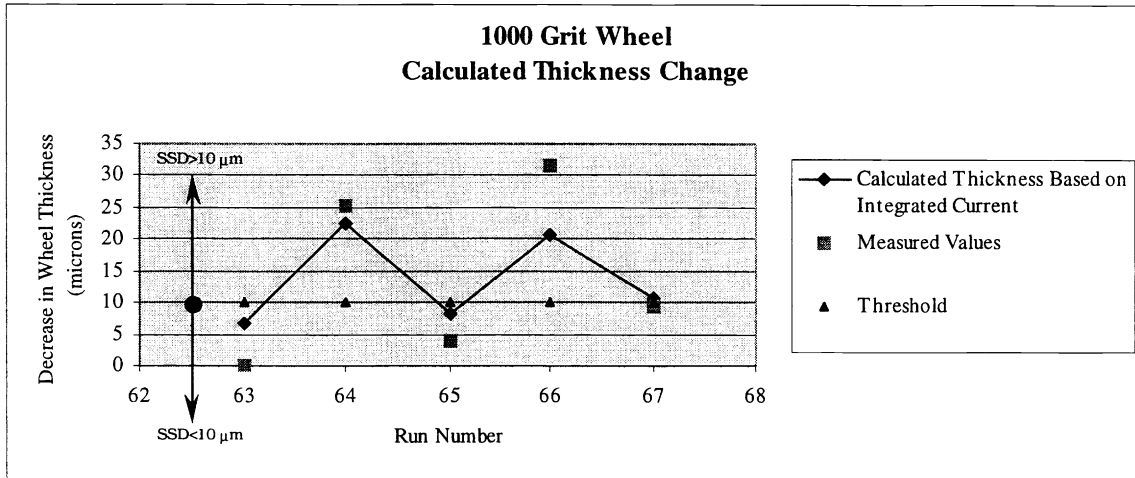
(Figure 3. 6.3 μm wheel thickness change. Run #63)



(Figure 4. 22.5 μm wheel thickness change. Run #64)

recognized as well as the once per table revolution in the increase in current indicating the removal of oxidation. The sub-surface damage for this run was typical ($< 10 \mu\text{m}$) for ELID grinding of phosphate. Figure four shows the same once per revolution effect, however, the current does exponentially decay until enough oxidation has built up on the wheel. This current profile is an indication of the oxidized and etched layer breaking down during the grinding cycle resulting in large sub-surface damage requiring re-grinding the surface. By integrating these current profiles the wheel thickness change can

be calculated (figure 5). The ability to measure the thickness change is difficult due to the size and access of the wheel. The measurements are based on four different locations on the wheel. If the wheel thickness change is greater than or equal to the grit size then cutting performance will degrade. When the wheel thickness change is kept below a certain threshold the sub-

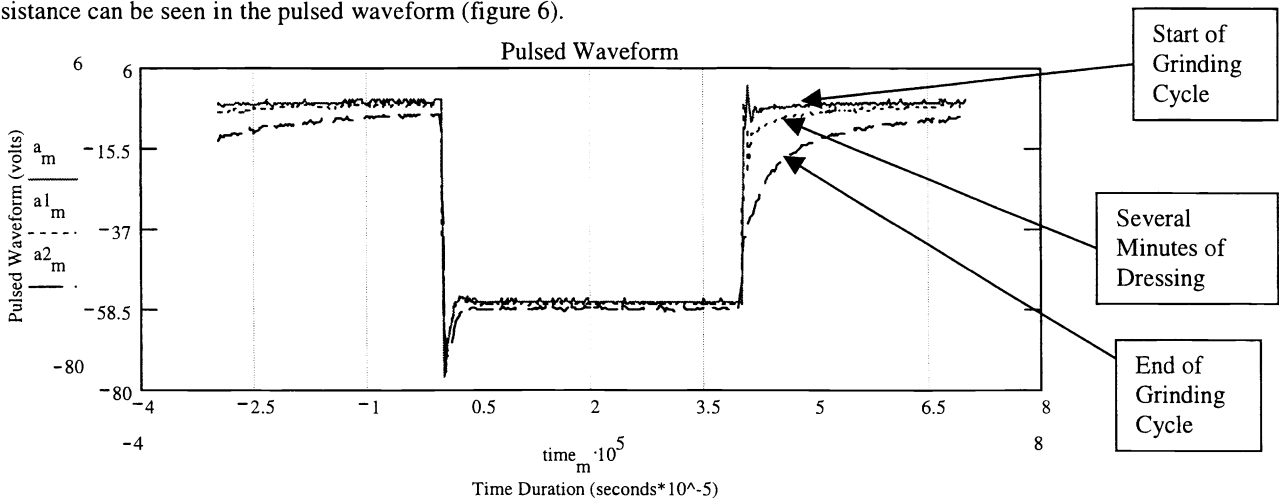


surface

(Figure 5.)

damage is kept to a minimum. To maintain a certain oxidation rate and current level there are several parameters for adjustment based on the oxidation rate equation. The voltage, current and electrode gap can all easily be varied to bring the oxidation rate into a regime where machining is most efficient.

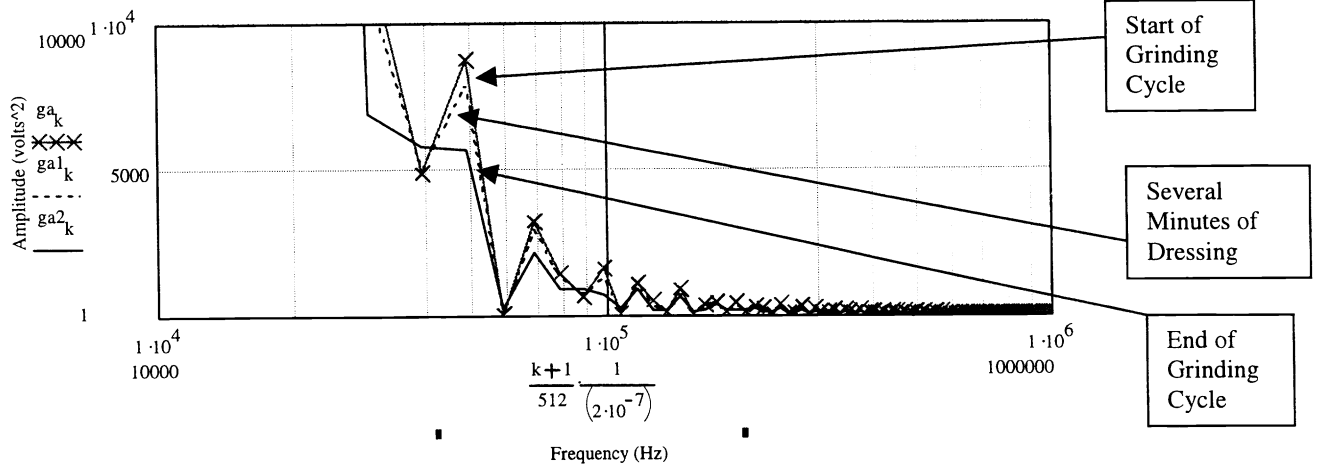
The power supply selected for this application has a built in control for switching from current mode, constant current and varying voltage, to voltage mode, constant voltage and varying current. In constant current mode the charge is a linear function of time. In constant voltage mode the charge is non-linear as described previously. The non-linear growth of the oxide layer is critical for the ELID process as described by Dr. Ohmori⁵. The effect of the oxide layer growth is a change in resistance in the wheel. The higher the current the lower the equivalent resistance of the wheel. These changes in wheel resistance can be seen in the pulsed waveform (figure 6).



(Figure 6. Three waveforms acquired during grinding)

As seen in figure 6 the waveform is changing based on the amount of time the dressing cycle has been applied to the wheel. The waveform at the start of the grinding cycle indicates the low resistance of the wheel in the non-oxidized state. As time progresses, oxidation thickens, the resistance rises and the off portion of the pulsed cycle begins to show signs of an increase in time to go back to zero. This discharge of the pulsed waveform can also be seen in the change in its frequency spectrum. The frequency spectrum of a square wave has a well defined signature. By looking at the frequency spectrum of each of the above waveforms a distinct change can be seen at several frequencies (figure 7). The DC supply is pulsed at 40 μseconds at

a 50% duty cycle. The frequency spectrum has a definite change in amplitude at around 49 kHz. For an increase in oxidation a decrease in amplitude at this frequency can be realized. By tracking this change one can effectively track the dynamics in the wheel.



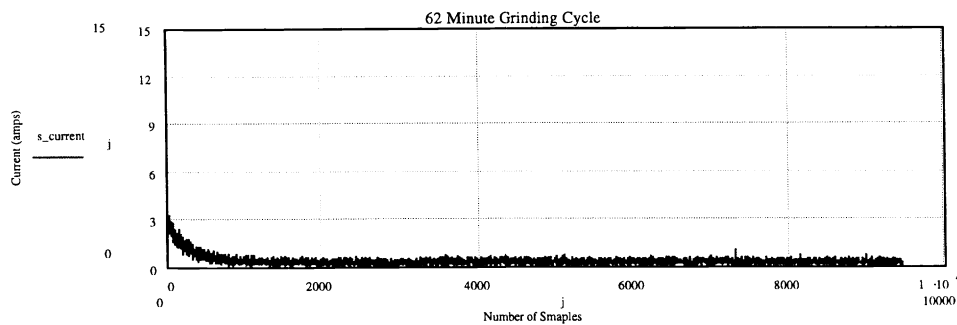
(Figure 7. Frequency spectrum)

By acquiring this information during a grinding cycle real time knowledge of the wheel oxidation can be obtained. Keeping the power supply in voltage mode so the oxidation can grow at a non-linear rate and reducing the amount of total current during the ELID cycle will create the ability to have a deterministic process. One way to achieve this is by controlling the down feed rate of the machine to balance the oxidation rate of the wheel by using the relative change in the frequency spectrum of the waveforms at a specific frequency.

During machining the pulsed waveform is acquired from a digital oscilloscope. The Fourier Transform is taken and the frequency spectrum is calculated. The amplitude of the pulsed waveform is $f(a)$ and $F(f(a))$ is the Fourier Transform of

$$FrequencySpectrum = |F(f(a))^2|$$

the amplitude. Based on previously machined parts a threshold is set for the amplitude of the frequency spectrum at 49 KHz. A control loop was developed to override the feed rate of the CNC controller. If the spectrum was above the threshold the feed rate would be slowed down and conversely if it was below it would speed up. As seen in figure 8 applying this technique as compare to figure three or four reduced the current profile. There are two things to notice; first the initial current level is reduced as compared to figure 3 and there are no increases in current during the dressing cycle as seen in figure 4.

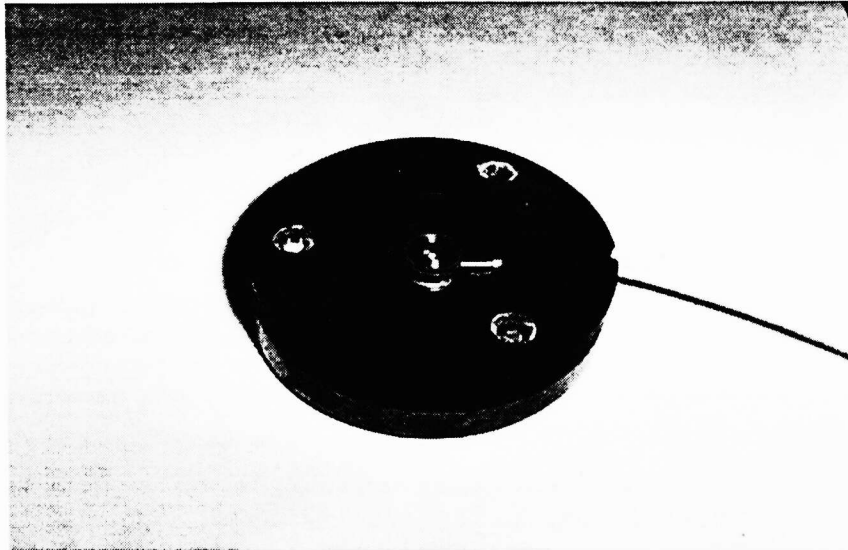


(Figure 8. Current waveform with control loop active)

The initial current level is reduced mainly from optimizing the electrode gap and adjusting the voltage based on the oxidation rate equation. The elimination of fluctuations in current is due to the control of the pulsed waveform.

3.0 Element support during ELID grinding

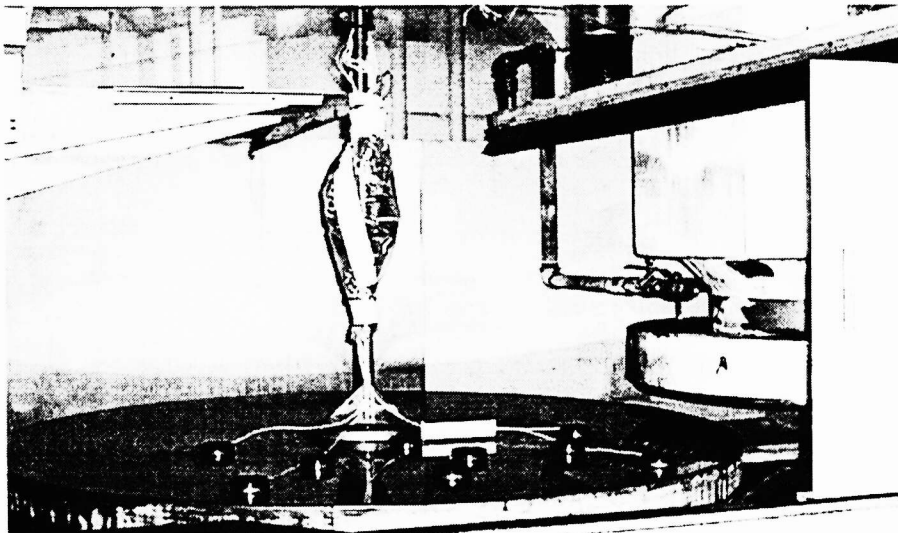
The main reasons for using ELID is to reduce fabrication time and cost as compared to loose abrasive grinding. To go from fixed abrasive grinding to polishing the surfaces needed to flat. The control loop was developed to address the sub-surface damage issues. So an in process part monitoring system was developed to obtain insight on the events taking place during grinding and how they affected surface flatness. The Toshiba grinder has a 60" diameter table to allow for multiple parts to be ground at once. Having more than one part on the table produces an intermittent cut. Having an intermittent cut causes part dynamics that are not noticed when the wheel is always in contact. Grinding experiments and post metrology indicate part motion during grinding. To obtain insight into these motions the optic support hardware was equipped with KAMAN eddy current gauges (figure 9). The purpose was to see what kind of substrate motion could be detected during grinding that could be attributed to part support.



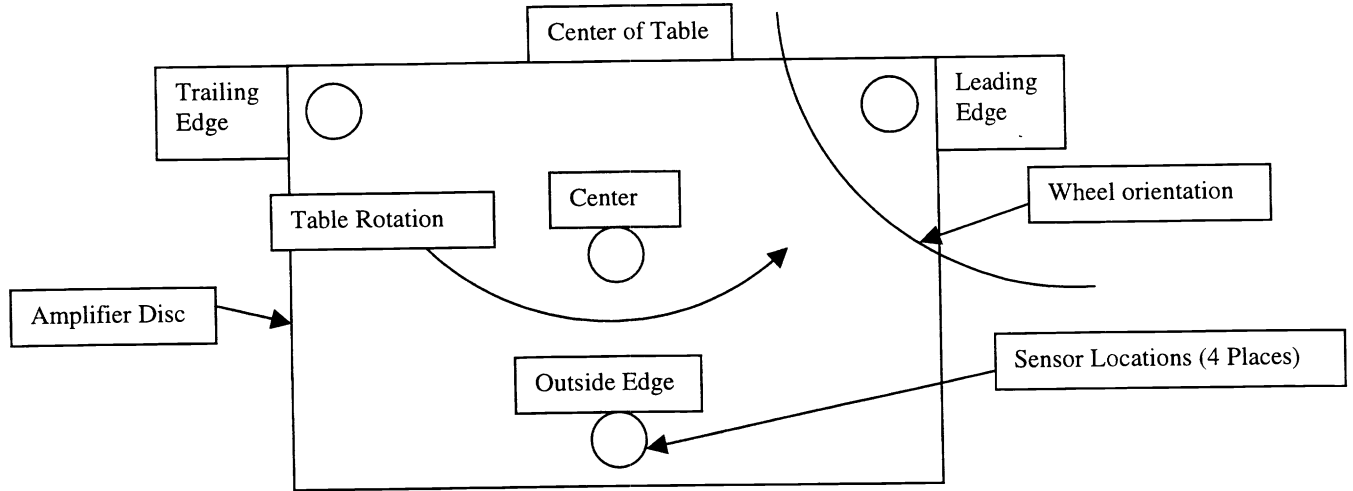
(Figure 9. KAMAN eddy current gauge mounted in an optic support puck)

There were four pucks instrumented with these sensors to measure in-situ part motion during ELID grinding. The four sensors were interfaced to a PC with a 12 bit A/D card for data acquisition. The rotary motion of the table was configured with a slip ring to get the electrical signal to the PC (figure 10).

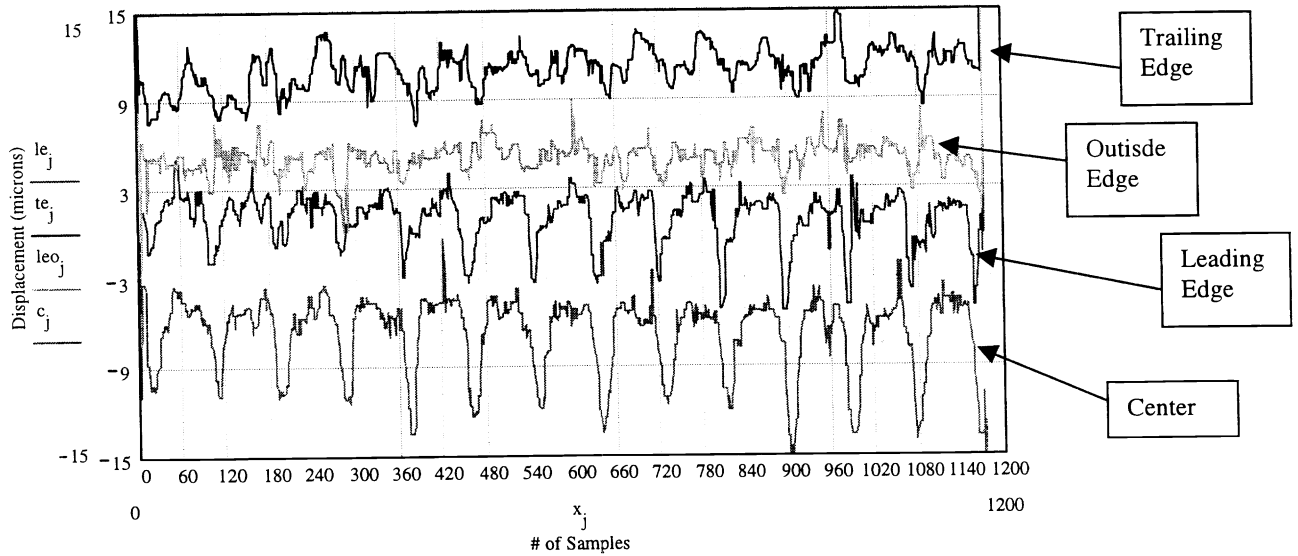
(Figure 10. Eddy current sensors and Slip ring arrangement on the Toshiba grinder)



The location of the sensors was changed during several different grinding sessions. Sensors were located at the corners and mid section of the optic (figure 10). The first feedback obtained from these sensors was corner duck away on the leading and trailing edges of the part (figure 11).



(Figure 10. Amplifier setup on Toshiba table)

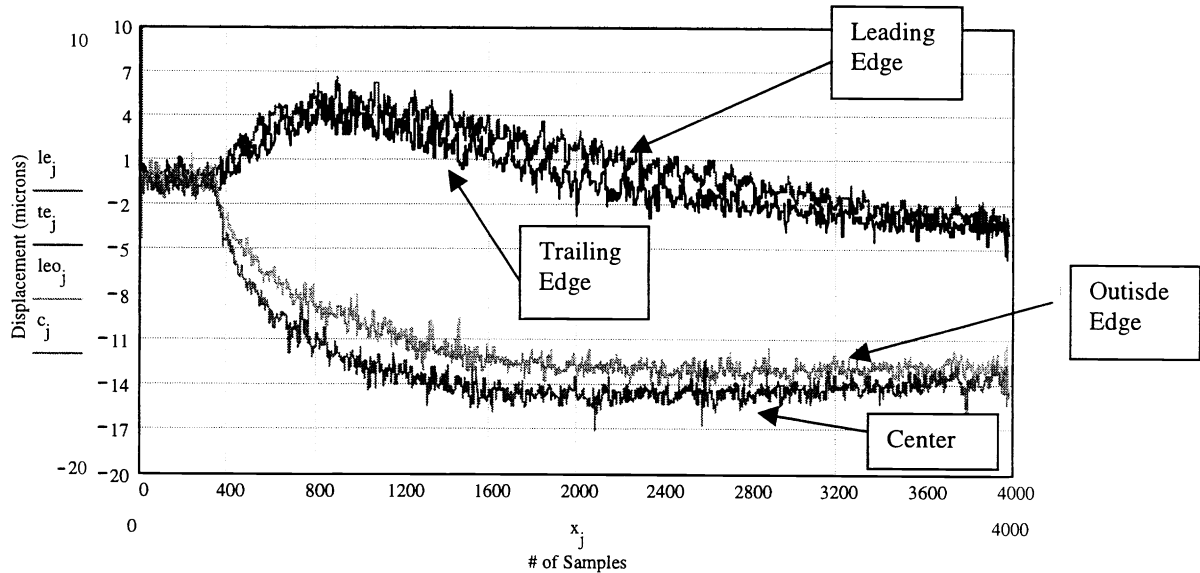


(Figure 11. Eddy current gauge response at leading and trailing edge of optic.)

The data confirms part motion during grinding. The most significant deflection during grinding is noticed in the center and at the leading edge. The optic is supported on six points. Uniform support by all six points is not possible so a point by point shimming is done in an attempt to approach even support. This approach is not adequate as seen by the data in figure 11. A multi-point support with adjustment is required that will give uniform support during grinding. Along with static and dynamic deflection concerns are thermal concerns. Phosphate laser glass has a high coefficient of thermal expansion, approximately 13 ppm/K, so part bending due to thermal gradients can be significant. A phosphate disc will bend approximately 14μm using a basic model for a simply supported beam¹⁰ with an axial gradient of 1 degree. Using the eddy

$$deflection = \frac{\alpha \Delta T a^2}{2t}$$

current sensors to determine the amount bending due to temperature effects was done by looking at the change in shape when one side is dry and the other is saturated with coolant. This test does not totally represent actually machining conditions, it was performed to determine if the thermal environment needed to be addressed. Figure 12 shows the same four locations of



an amplifier slab that are changing due to thermal gradients. The effect of coolant being poured over the top and not on the bottom shows the top surface cooling, which should make the disc concave. This is indicated by the center sensor displacement going down and the edges going up. The part stabilizes after several minutes with a total change from center to edge of about 10 μm p-p.

4.0 Conclusion

By incorporating process monitors during ELID grinding the electrolytic process can be controlled. The result of this control has allowed the successful implementation of this process on a large scale machine. Waveform dynamics is directly related to ELID performance under the conditions described in this paper. Monitoring part deflection during grinding has given insight into machining dynamics on phosphate amplifier discs.

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