Variation Reduction of a Closed-Loop Precision Ceramic Micromachining Process

by

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B.S. Metallurgical Engineering, University of Minnesota (1982)

Submitted to the Sloan School of Management and the
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in Partial Fullfillment of the Requirements for the Degrees of

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Abstract

This report details the investigation of the micromachining of a TiC•Al_2O_3 ceramic using a closed-loop lapping process. Currently the micromachining process laps a ceramic bar with only a priori flatness adjustment. Bar flatness is adjusted prior to the lap using optical measurement of lithography targets. The average value of a critical dimension determines lap completion. The critical dimension is determined with an embedded electronic lapping guide (ELG). The problem with this technique, as it is currently employed, is high product loss due to large variance of the critical dimension across the bar. A six microinch standard deviation is desired. Any product above or below specified critical dimension limits are scrapped, so the variance reduction directly impacts immediate and downstream process yields. An alternative approach is proposed using electrostrictive actuators in a closed control loop to deform the bar during lap processing. The closed-loop lapping (CLL) process significantly decreases critical dimension process variance.

Thesis Supervisors
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> *The important thing is to not to stop questioning. Curiosity has its own reasons for existing. One cannot help but be in awe when he contemplates the mysteries of eternity, of life, of the marvelous structure of reality. It is enough if one tries to comprehend a little of this mystery every day.*
>
> Albert Einstein

> *Only those who attempt the absurd... will achieve the impossible. I think ...I think it's in my basement...Let me go upstairs and check.*
>
> M. C. Escher

> *A child of five would understand this. Send someone to fetch a child of five.*
>
> Groucho Marx

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List of Symbols

R = electrical resistance of a conductor between points a and b (Ω)
V = voltage potential from point a to b (volts)
i = current (amperes)
ρ = material resistivity ($\Omega \bullet$cm)
E = electric field (volts/cm)
l = length of conductor (cm)
j = current density (amperes/cm^2)
S = conductance (siemens)
A = area of conductor = width x thickness (cm^2)
w = width of conductor (cm)
t = thickness of conductor (cm)
K_t = spring constant of a transfer tool beam (lbs/in)
E_t = transfer tool modulus of elasticity (psi)
L_t = length of transfer tool beam (in)
b_t = transfer tool width (in)
h_t = transfer tool beam height (in)
K_p = spring constant of a transfer pin (lbs/in)
E_p = transfer pin modulus of elasticity (psi)
L_p = length of transfer pin (in)
A_p = transfer pin area (in^2)
d_p = transfer pin diameter (in)
K_c = spring constant of ceramic cap (lbs/in)
E_c = ceramic cap modulus of elasticity (psi)
L_c = length of ceramic cap (in)
A_c = ceramic cap area (in^2)
K_a = spring constant of electrostrictive actuator (lbs/in)
E_a = electrostrictive actuator modulus of elasticity (psi)
L_a = length of electrostrictive actuator (in)
A_a = electrostrictive actuator area (in^2)
d_a = electrostrictive actuator diameter (in)
K_{sys} = spring constant of actuator/transfer tool system (lbs/in)
F_{sys} = force of actuator/transfer tool system (lbs)
δ_a = actuator deflection (in)
δ_t = transfer tool deflection (in)
x = strain (in)
ξ = proportionality constant
ζ = proportionality constant
D = dielectric displacement (in)
ℓ_1, ℓ_2 = length of actuators 1 and 2 (in)
d = displacement loss in pin linkage (in)

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It is easier to resist at the beginning than at the end.
Leonardo da Vinci

Chapter 1: Introduction

Problem

Flatness control of a TiC•Al_2O_3 ceramic bar is critical for microcomponent quality and manufacturing yield. Precision dimension control is obtained with a lapping process. In the lapping process, a "row" of ceramic microcomponents (sliders) is mounted on a tool bar (Figure 1-1), the tool bar is mounted in a holding block, and several holding blocks are processed on a lap machine.

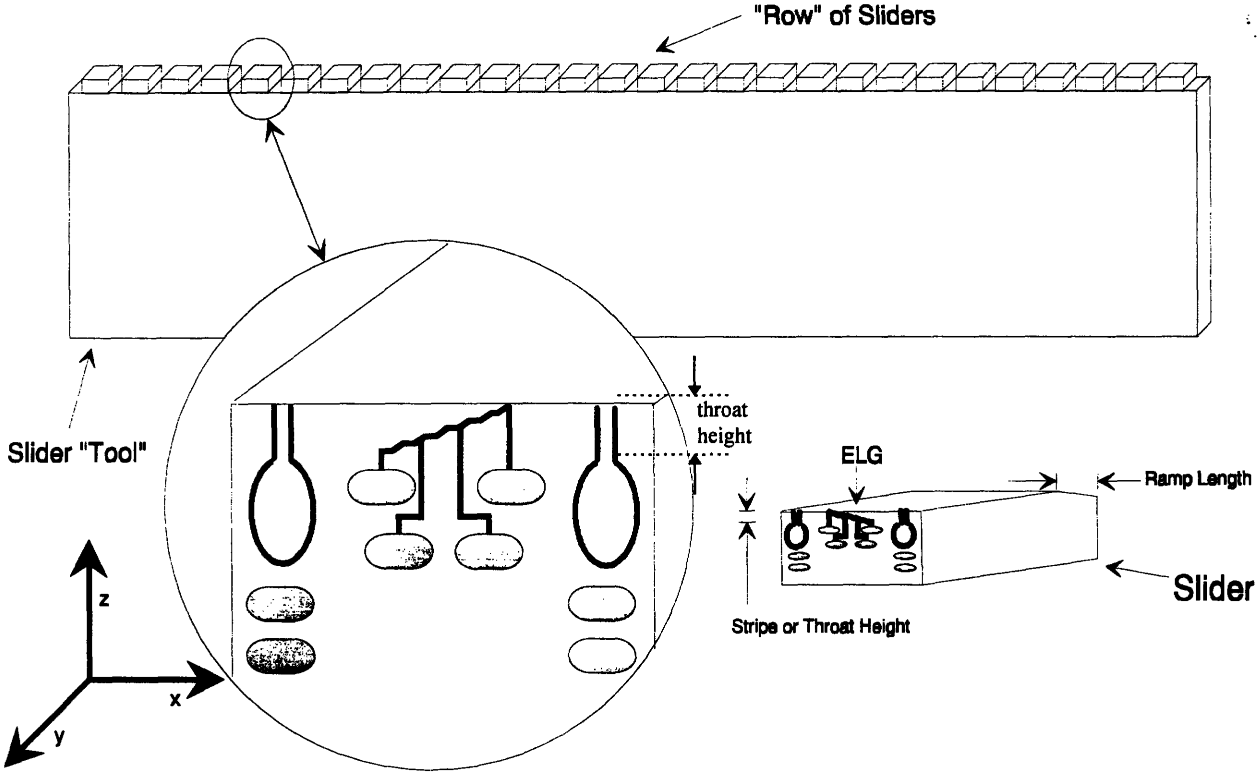

Figure 1-1. Row of ceramic sliders mounted on a lapping tool bar.

Each slider must be lapped to a specific critical z dimension. Industry leaders achieve throat height standard deviations of 5 to 8 microinches (u"), while second tier players achieve 8 - 12 u" and some only achieve 12 - 15 u". "World class" flatness is equivalent to a football field being level to 0 +/- 0.01" across its entire 100 yard length.

The critical engineering issues are: throat height, surface flatness (x & y direction), ramp length, and ramp angle. Critical operational issues include: throughput time (TPT), cost, equipment development time, product variation, operator learning, equipment uptime and technology transfer.

The flatness of the current tool bar can only be adjusted prior to lap, with a two position flatness correction. This pre-lap adjustment is a capable process for older product technology, but it is not capable for leading edge or near future products. Competitive pressures dictate lower cost, higher yield, and higher quality, with flatness variation being the largest lever for improvement.

Background

Ceramic surface lapping is used in several industries including optical lens manufacturing, silicon wafer planarization, metallurgical sample preparation, and recording head manufacturing. Lapping equipment may be planetary or linear in design. An abrasion slurry, usually polycrystalline diamond, is embedded in a large rotating wheel. A force is applied onto the specimen and ceramic is removed through abrasion.

This paper is concerned specifically with the precision lapping of a row of $TiC{\bullet}Al_2O_3$ ceramic bars. Precision lapping of a $TiC{\bullet}Al_2O_3$ substrate row is the standard method of achieving specific electrical performance - magneto restrictive (MR) stripe height or inductive thin film throat height (both will be now be referred to as throat height) in this particular electronic component manufacturing industry.

The vast majority of performance lapping equipment is produced by the component manufacturer, with process optimization and integration also occurring with the end-user. In most cases a diamond slurry is the $TiC{\bullet}Al_2O_3$ lapping medium with a lubricant. A planetary or semi-planetary system is used to maximize flatness, in a fashion similar to wafer polish in the semiconductor industry or optical element polishing. A differentiating element of lapping in this industry is the use of thin film resistors to electrically determine end-points.

The success of the lap process is dependent upon minimizing variation across the ceramic row and stopping the process at a specific electronic component length. This is accomplished with the use of thin film resistors. A standard lap process uses resistance data to correct for bar taper and relative lap rate. An enhanced lap process additionally uses the resistance for closed-loop row deflection adjustment.

A major variable in TiC•Al_2O_3 row lapping is the number of *in-situ* deflection points across the row. A single deflection point located in the center of the row is able to correct for some simple bow shapes, while a two-point deflection scheme allows for correction of S-shapes. A three point defection scheme is the most advanced method currently used in high volume production as it allows for correction of the majority of bar bows.

Goal

The goal of this paper is to examine engineering and operational issues specific to the domain of TiC•Al_2O_3 lapping in a high volume manufacturing environment. A novel approach of using a closed-loop lapping (CLL) process will be examined in detail. Process variation minimization methodologies during the development, technology transfer, and high volume manufacturing phases will be discussed.

Approach

This paper describes the current TiC•Al_2O_3 row lap process and the particular issues associated with this process. An alternative process using closed loop lapping is described. Critical engineering metrics of the standard and the new process are quantified and contrasted. The vital role that information technology plays in a process engineering organization is discussed along with equipment economic assessment, process simulation modeling, and key operational issues that arose during various phases of the technology development and transfer process.

> *It is not the end, it is even not the beginning of the end. It is perhaps the end of the beginning.*
>
> *Sir Winston Churchill*

That we can comprehend the little we know already is mindboggling in itself.
Tom Gates

Chapter 2: Background and Theory

Ceramic Row Fabrication

The end user purchases the $TiC{\bullet}Al_2O_3$ ceramic in the form of a wafer; either a 2" - 4" square or a 3" - 6" round wafer. Electrical components are fabricated on the front surface of the wafer with various chemical vapor deposition, metallization, lithography, and etch process steps.

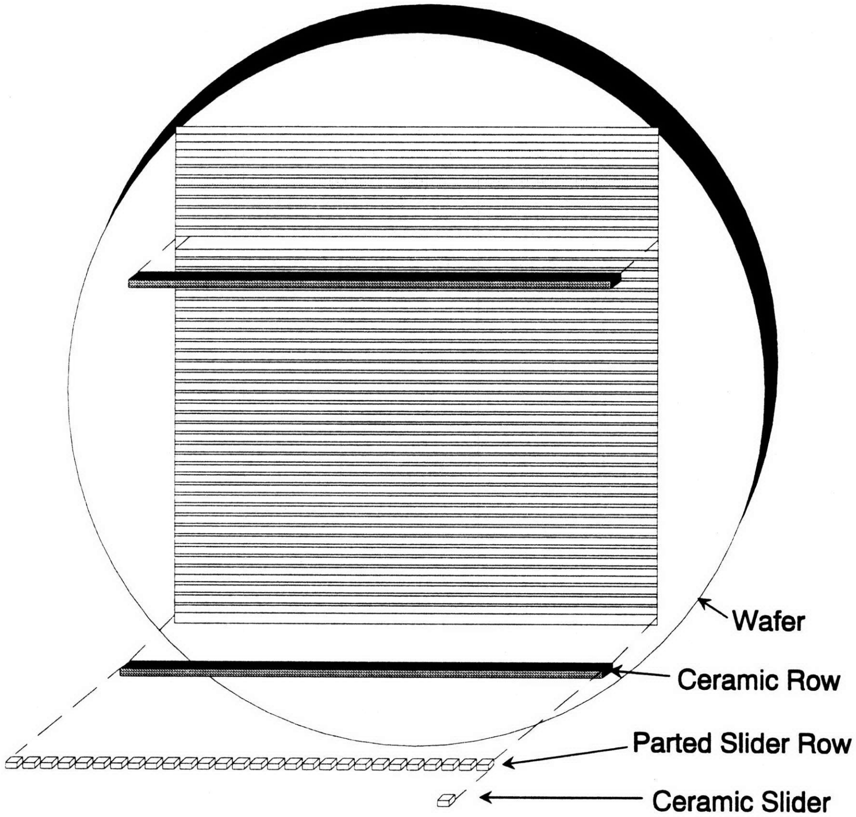

Figure 2-1. Slider rows cut from a $TiC{\bullet}Al_2O_3$ wafer.

The wafer is cut into rows (Figure 2-1) with a diamond grinding wheel, and the row is mounted on a tool bar (Figure 1-1) with an adhesive. Each row contains many individual ceramic microcomponents (sliders), with quantity dependent upon the product generation and design requirements. The individual sliders are separated from each other during a diamond wheel slicing operation.

Row Bow Adjustment

Process Description

The bow adjustment, or *Row Bow* process, flattens the ceramic bar before lap processing commences. The row of ceramic parts has been mounted on a tool which contains both a left and right bow adjustment screw. This screw can be engaged or disengaged to change the deflection of the bar (Figure 2-3), and hence the slider row bow.

Lithography defines an alignment target on the front surface of each slider during wafer processing. Optical recognition systems measure the relative position of each slider target along the tool row. Left and right "bow", or divergence from zero throat flatness, is then calculated for each row and a software algorithm calculates the optimum screw adjustment for the operator to make. The bow is adjusted in an iterative fashion within a predetermined flatness specification - a tighter specification produces better outgoing flatness, but at a productivity cost.

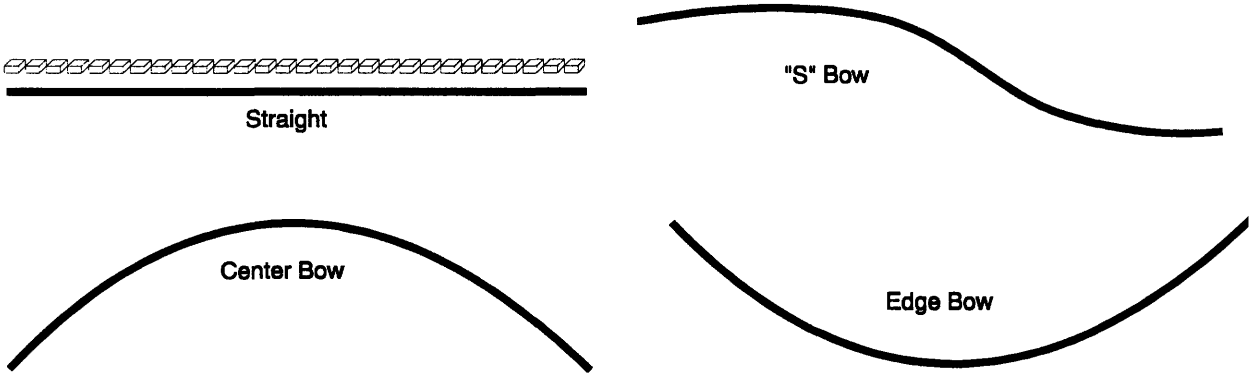

Figure 2-2. Illustration of various bow shapes.

A two point adjustment tool (Figure 2-3) can easily flatten a center (or negative) bow shape with positional deflections applied to the two edges. An edge (or positive) bow can only be negated with a decrease in edge deflection or "backing off" with a negative edge deflection adjustment. Negative deflection requires a force to be present against the adjustment screw, thus the requirement of a pre-set negative deflection in the tools. Each side of a tool behaves as a simple beam. When a force is applied to the beam, it deflects a given amount dependent upon its mechanical spring constant.

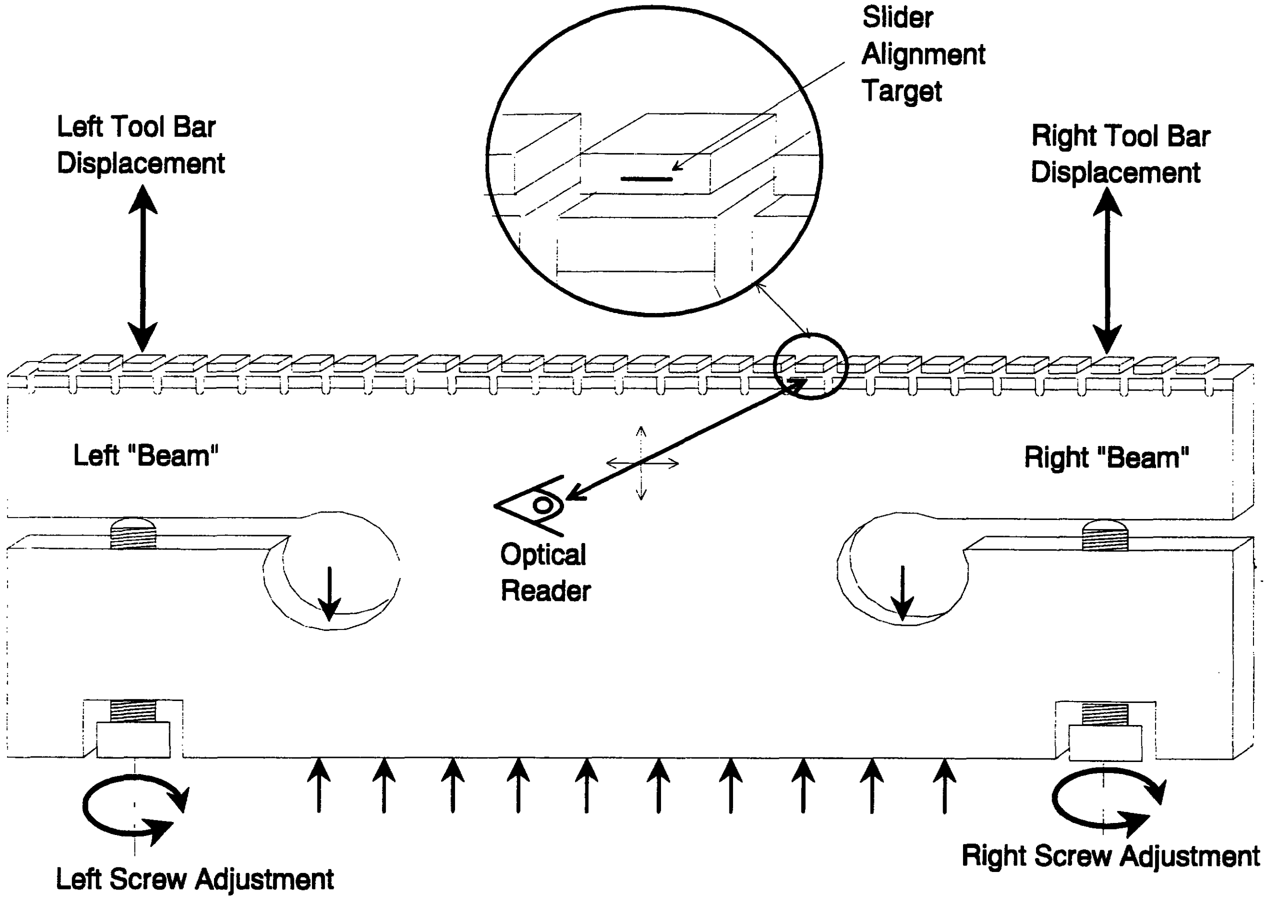

Figure 2-3. Row Bow adjustment of tool flatness.

Equipment Description

Internally manufactured Row Bow optical analysis equipment is used to measure the bow of the slider row prior to ceramic lap. Optics magnify and focus the deposited surface of the slider. Staging with motors and precision bearings is used to scan the length of the tool, while the optics view each of the sliders. On the surface of each slider is a slider alignment target. The positional offset of each slider is calculated with a control computer, and adjustment values are output to the operator.

Process and Equipment Problems

Equipment problems at Row Bow include screw thread wearing and optics misadjustment. Process problems include inaccurate measurement of position, poor operator adjustment procedure, and degraded incoming tool pre-flatness. The accuracy of the relative slider position can be impacted by lithography target definition and etch profile, bar surface contamination, and Row Bow equipment performance. Desired operator adjustment is prompted by the Row Bow software - there is no feedback loop to ensure that the operator performs the task to the given specification. Screw backlash causes additional problems for some operators. Factors that impact minimum bow include tool surface burrs[i], mechanical abuse (over-tightening of screws), and bad incoming flatness due to the glue process.

Ceramic Lap

Lap Process

Fine mechanical abrasion of the $TiC \bullet Al_2O_3$ slider surface is accomplished with either a planetary lap design [Figure 2-4] or a linear "tone-arm" style design [Figure 2-5]. In the planetary design a disc rotates out-of-sync with a large rotating lap plate. The diamond slurry/lubricant abrasion mixture is applied to the lap plate surface before the lap starts and also periodically during the lap.

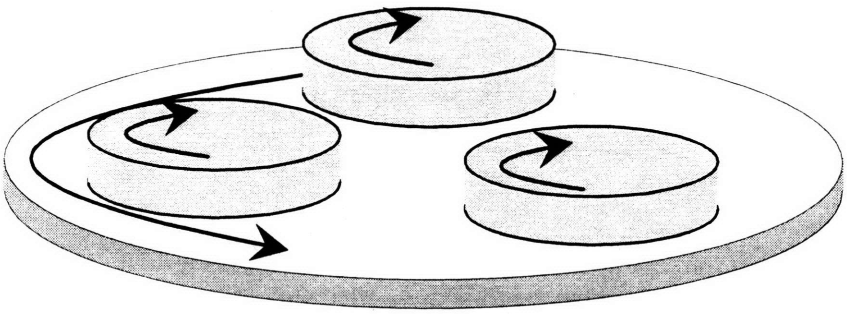

Figure 2-4. Planetary design for uniform ceramic lap.

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[i] The issue of surface burrs can be corrected with the use of ceramic tools but the cost per tool is high. Ceramic tools will usually chip rather than undergo plastic deformation.

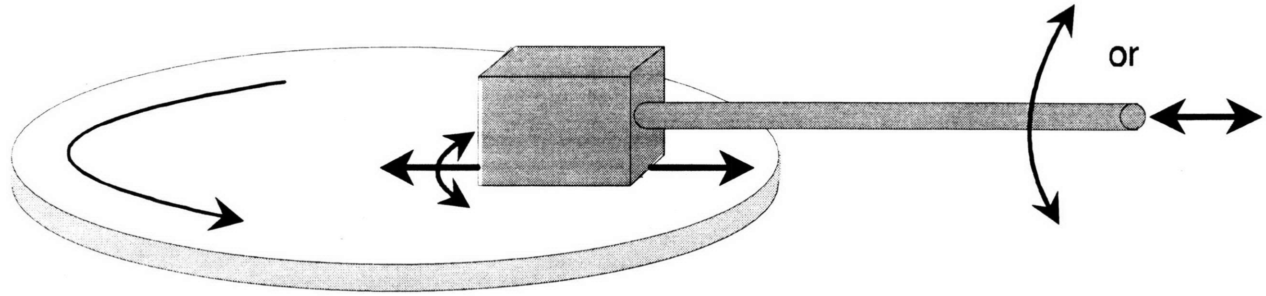


Figure 2-5. Linear lapping system.

Mechanical abrasion removes $TiC \bullet Al_2O_3$ until the desired throat height length is reached, as indicated by an in-line process monitor. Previous generation process monitors included digital optical switches, optical lapping guides (OLGs), and early design electronic lapping guides (ELGs). Newer generation ELGs consist of both analog and digital resistors that are constructed during wafer thin-film processing. The resistance of both resistor types changes during the lap process; the analog resistor as a function of resistor width decrease [Figure 2-6], and the digital resistors as a function of digital circuit breaks [Figure 2-7].

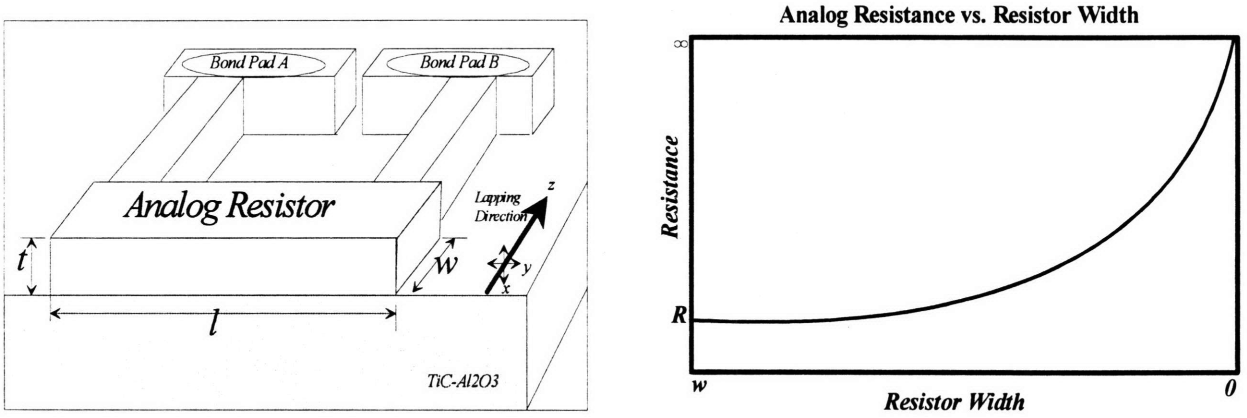


Figure 2-6. a) Typical analog resistor structure, b) Resistance vs. lap length.

The analog resistors can have lower positional accuracy than digital resistors because of thin film stoichiometry and thickness variances across a wafer. Using the geometry defined in Figure 2-6 the ELG resistance is equal to the product of the thin film structure resistivity (ρ) and length (l) divided by width (w) and thickness (t).

$$R = \frac{V_{ab}}{i} = \frac{\int_a^b E\,dl}{\int j\,dS} = \frac{El}{jA} = \rho \frac{l}{A} = \rho \frac{l}{wt}$$

Equation 2-1. ELG analog resistance as a function of thin film width, thickness, length and resistivity.

Digital switches [Figure 2-7] or resistors should be defined with the same lithography steps as the critical electronic component. Positional errors result from within reticle field errors and field-to-field alignment stepping errors. When a digital switch or shunt is lapped through, the resistance is increased by the shunts parallel resistor (R2, R3, R4 etc.) value. The shunt breakthrough results in a step increase in ELG resistance, which is correlated to a position (d1, d2, d3, etc.) relative to the critical electronic component minimum dimension (throat height).

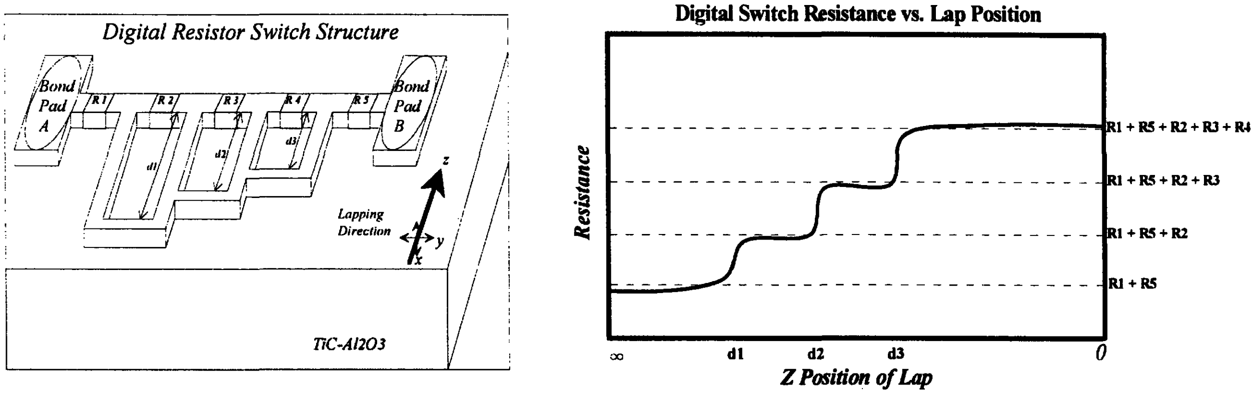


Figure 2-7. a) Typical digital switch structure, b) Resistance step increases vs. lap position.

Several different digital switch layouts result in the same positional information. The number of digital shunts is limited by desired surface area allocated for this monitor. Usually, the accurate digital resistors are used to calibrate the continuous signal analog resistors, but some processes use only analog resistors. Resistance values are converted into inductive throat height or MR stripe height through correlation tables and provide data for end-point feedback, row parallelism (i.e. taper) adjustment, and *in-situ* row bow correction.

The row average throat height is calculated from the individual throat height data Lapping is terminated when the row average throat height reaches the specified product target. The row stripe height is quantified during the lap process, and parallelism is corrected. No adjustment is made in the standard process for non-linear bows. The taper adjustment is done with the use of pneumatic plungers applying forces on the ends of the bar.

Lapping Equipment

A standard ceramic lapper includes the following functional components: mechanical process fixtures; input and output data devices; electrical, pneumatic air and diamond slurry delivery; waste fluid collection; and a computer for process control. Major process components [Figure 2-8] include a large rotating plate on which a puck rotates. Inserted into this puck are the module blocks, which in turn hold the transfer tools. Attached to the transfer tool is the ceramic row.

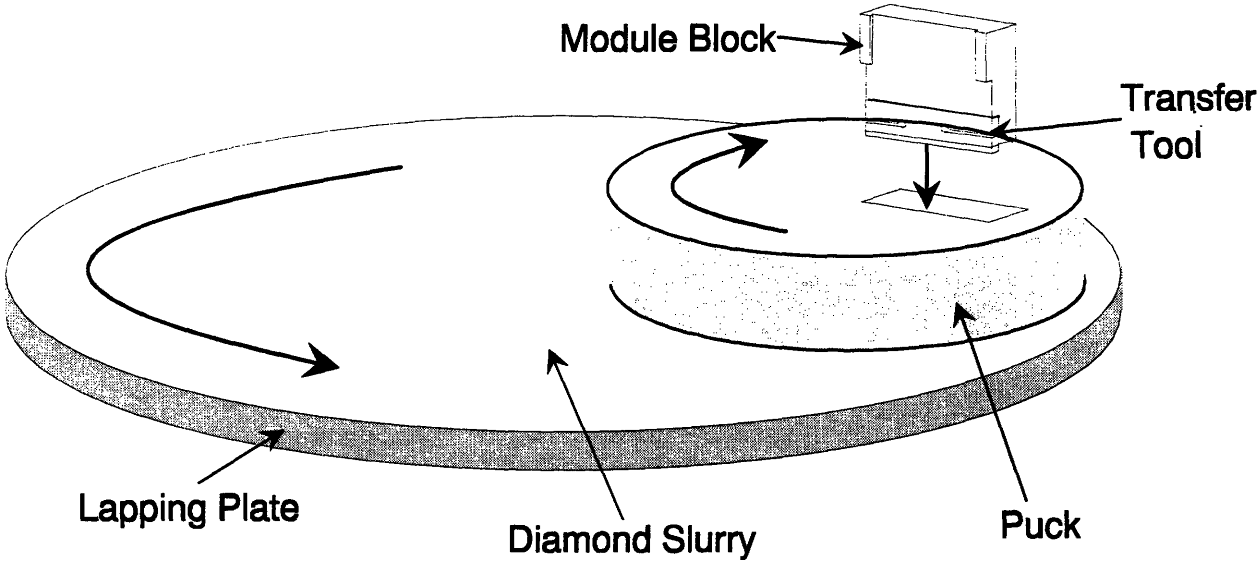


Figure 2-8. Mechanical lapping components.

Electrical components of the lap system include safety interlocks, AD and DA converters, ELG data boards, pneumatic control boards, and a computer for process and equipment monitoring. Process data is automatically uploaded after each process run. Operators, technicians, and engineers monitor the process through various windows on the computer.

Lapping Module Block Assembly

The lap module block, as described below, was a primary component of the overall lap variation investigation. The standard process module block consists of a stainless steel support structure, a transfer tool, electrical flex print and connectors, and a mechanical and electrical cover. Dimensional control of the module block is critical.

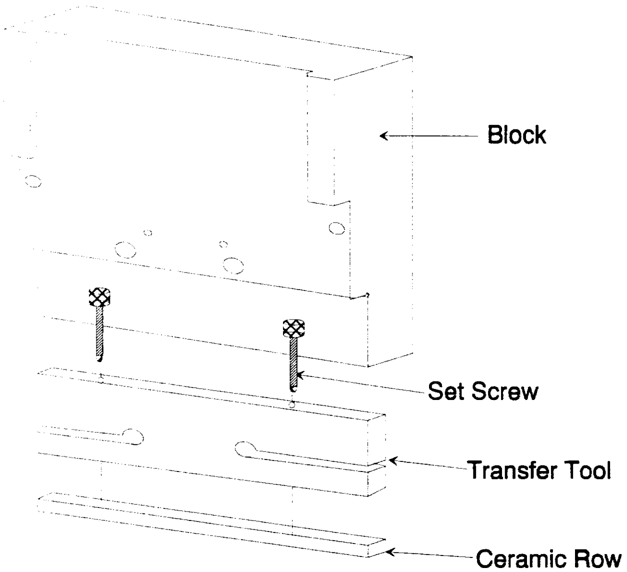


Figure 2-9. Standard process module block.

The ceramic row is adhered to the transfer tool, which is inserted into the module block, and mechanically held in place with a cover. Next, several resistors are bonded to the flex print with a fine wire bonder. The module block is then inserted into a holding mechanism, and electrically connected to the lapper. Pneumatic valves apply force to left and right topside of the module block for taper control.

Lap Process and Equipment Problems

Problems in the lap process include large throat height variation across a bar and poor quality incoming ELGs. The throat height variance is being addressed with the work described in this thesis. Poor incoming ELG quality is product and technology specific and is being addressed in other task forces. End-point control is currently not an issue. Equipment related problems include mishandling of module blocks, dimensional control, spring wear-out in the puck, and lap plate flatness control.

Ramping Process

A shallow ramp (Figure 2-10) must be micromachined into a slider on the end opposite of the electronic circuitry. This ramp process may either be completed sequentially to fine lap on the same equipment or as another process step after fine lap is completed. Equipment capabilities of the standard process dictate whether the ramp process is performed as an additional step.

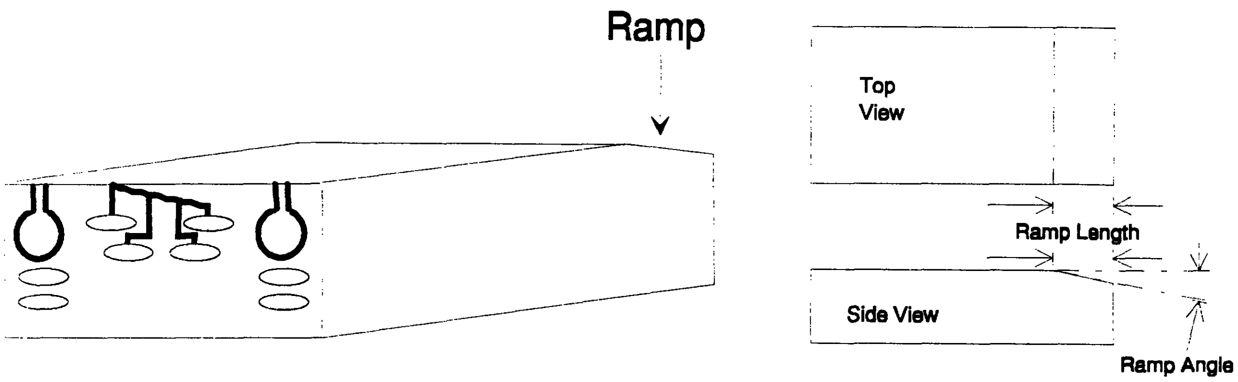


Figure 2-10. Slider ramp length and ramp angle.

The ramp process is very similar to the fine lap process in that a planetary lapper with a diamond slurry is used for material removal. The ramp process is different in that no ELGs are used for endpoint or taper analysis. An operator quantitatively checks ramp length with an optical analysis technique, and qualitatively checks ramp flatness. Process problems result from poor lapping plate flatness, operator procedural errors, and various problems associated with puck degradation.

Precision Mechanical Displacement Actuators

Actuator displacement resolution, range, repeatability, and response time are critical to precision micromachining performance. Displacement resolution must be much less than the intended tolerance control of the machining process. Displacement range must be large enough to allow a robust process capability. The actuation must be repeatable with the given control loop. Response time can be critical if the actuator movement is much slower than the machining process. The actuator must be able to apply enough force to meet the design specifications. High voltage can be a human safety issue, and may cause electrical design problems, so the required actuator voltage must be as low as possible. Cost and commercial availability are also relevant issues in the consideration of what type of actuator to use in a system design.

Types of Actuators

Several styles of commercially available actuators were analyzed with literature searches and/or vendor discussions. Stepping motor and voice coil actuators had many positive attributes for lapping but were deficient for processing because of the separate ramp operation. Paraffin thermal Actuators have large linear displacements but relatively slow response time, large physical size, and are a poor match for the off-line ramp process. Electrostrictive actuators meet the given boundary conditions needed for this process and are commercially available. Piezoelectric actuators were also viable for most boundary conditions except non *in-situ* ramping. If an *in-situ* ramp process is developed then piezoelectric actuators will become a less costly actuator choice.

Typical Applications

Electrostrictive actuators are used in many diverse applications. Uchino [72] describes the three main application fields as positioners, motors, and vibration suppressers. Electrostrictive actuators were used as the primary positioner in the closed loop ceramic lapping discussed in this thesis. Analytical tools such as electron microscopes use these actuators for precise stage positioning. Piezoelectric or electrostrictive actuators are used as motors in such diverse applications as pumps, fans, ultrasonic humidifiers and knives. Semiconductor lithography equipment uses these actuators to achieve high positioning accuracy (< 0.1 micron). High precision manufacturing systems may use the actuators for vibration control, laser positioning, and stage movement. Deformable mirrors use the actuators for aberration correction [20] such as the Hubble Space Telescope fix.

Piezoelectric vs. Electrostrictive Actuation

Electric Field vs. Crystal Lattice Displacement

The ionic-covalent chemical bonding of most ceramic materials results in the maximum packing density of opposite charged ions while preserving electrical neutrality. Of the 32 classes of crystals, 20 have one or more polar axes and thus can exhibit piezoelectricity, pyroelectricity and ferroelectricity properties [5,28,46]. Piezoelectric ceramics possess large electric dipole moments that can be aligned in an electric field below the material's Curie temperature. Lead-zirconate-titanate (PZT) is the most common ceramic used in piezoelectric actuators. Pyroelectric effect occurs when a change in temperature creates electric charge. Ferroelectricity is the spontaneous alignment of dipoles which may also result in a crystallographic phase change from a non-polar lattice to a polar lattice. Electrostriction is the change in shape of a material due to the application of an electric field across the material. If the strain (x) is proportional to the square of the applied electric field (E) it is known as the electrostrictive effect while piezoelectric materials strain is directly proportional to the applied field. Lead-magnesium-niobate [$Pb(Mg_{1/3}Nb_{2/3})O_3$], or PMN, is a commonly researched electrostrictive ceramic.

$$x = \xi \cdot E^2 \quad \text{and} \quad x = \zeta \cdot D^2$$

Equation 2-2. Electrostrictive strain as a function of the square of the electric field where x is strain, E is the applied electric field, D is the dielectric displacement.

Electrostrictive actuators have many advantages over piezoelectric actuators. Both actuator types have accuracy less than 0.01 um, high response time (10 usec), high generative force and low driving power. In addition the electrostrictive actuator can have strains up to 0.1% with very low hysteresis [72]. PMN actuators operate at low voltages, show minimal aging or creep, have low thermal expansion, and can have small physical dimensions [17,48,71,77,81].

Actuator Design and Fabrication

Piezoelectric and electrostrictive actuator fabrication use capacitor manufacturing technology. Ceramic mixing powders are carefully measured and adjusted to achieve desired stoichiometries. Binders such as polyvinyl alcohol are added in order to aide subsequent processing. The mixture is formed into thin sheets which are then cut into the final actuator sections - the diameter can be altered significantly depending upon the required application. The individual sections are stacked together with pick and place equipment - the actuator may have 10 - 300 stacked sections dependent upon force and extension design requirements. Sintering of the stack removes the binder from the ceramic solution and improves metal/ceramic interface properties. The electromechanical ceramic is placed between two electrodes [Figure 2-11], and an electric field is applied across the dielectric.

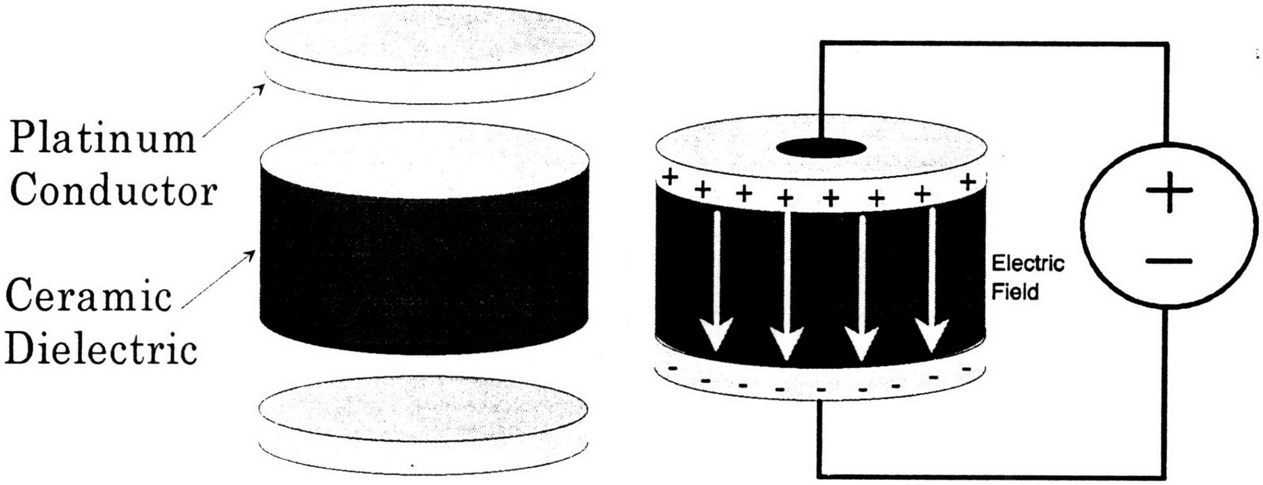


Figure 2-11. Ceramic dielectric with electric field bias conductor plates.

Strain is proportional to the voltage per unit length of piezoelectric dielectric, and to the square of the electric field for electrostrictive dielectrics; a thinner ceramic section will produce greater displacement for a given voltage. Final actuator displacement is dependent upon applied voltage and number of individual dielectric disks. The CLL equipment has voltage supply drive boards that are limited to 150 volts, which makes the thin dielectric stacked capacitor actuator an ideal match for this design. Figure 2-12 demonstrates how the parallel electrical connection of alternate conductor plates on each side of the actuator provides a mechanical series system. The displacement $l_2 - l_1$ is achieved on the multi-stack actuator when 150 volts is applied with a parallel electrical connection.

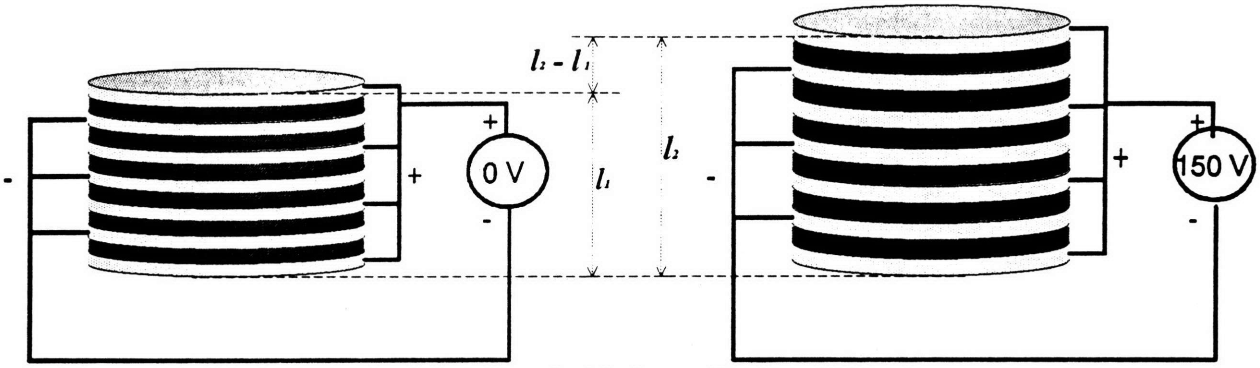


Figure 2-12 Displacement $l_2 - l_1$ is achieved with the application of 150 volts.

Mechanical Amplification Techniques

Several different styles of mechanical amplifiers are discussed in literature [8,42,49,51,53,66]. Several different styles are utilized in high displacement/low force applications such as ink jet printers. "Moonies" mechanical displacement amplifiers are used for medium force applications [49].

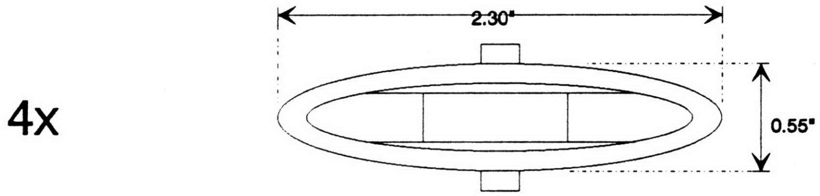


Figure 2-13. "Moonie" style 4x amplifier.

The moonie aspect ratio determines amplification. An increase in length results in higher displacement, but the force is proportionately decreased. A 2x amplifier as shown in Figure 2-14 was designed for later investigation of displacement and force.

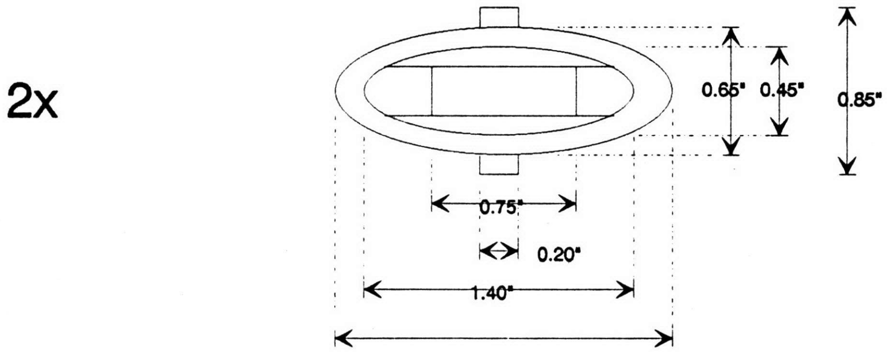


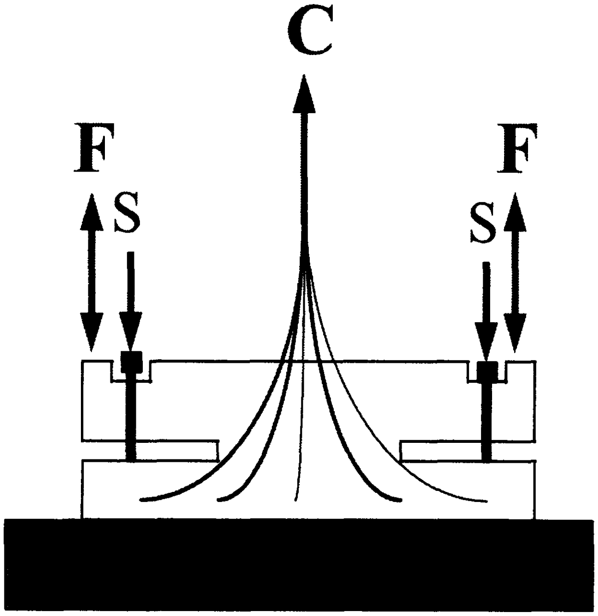
Figure 2-14. Actuator 2x mechanical amplification device.

... Though this be madness, yet there is method in't.
William Shakespeare

Chapter 3: Approach and Methodology

Closed-Loop Lapping

Closed-loop lapping (CLL) was employed to reduce row thickness variance during ceramic processing. Figures 3-1 and 3-2 graphically illustrate the differences between the standard and the closed loop process.



C = Computer for Resistor Data Analysis

F = Left or Right Penumatic Force for Taper Adjustment

S = Left or Right Set Screw for Row Bow Preadjust

Figure 3-1. Schematic of standard lap process.

The bar flatness is adjusted in the standard process with an iterative set screw adjustment at the row bow operation. Throat height data from only a few resistor pairs are analyzed by the process computer during the lap and pneumatic forces are adjusted to correct for row tapering. The resistance data also dictates process completion.

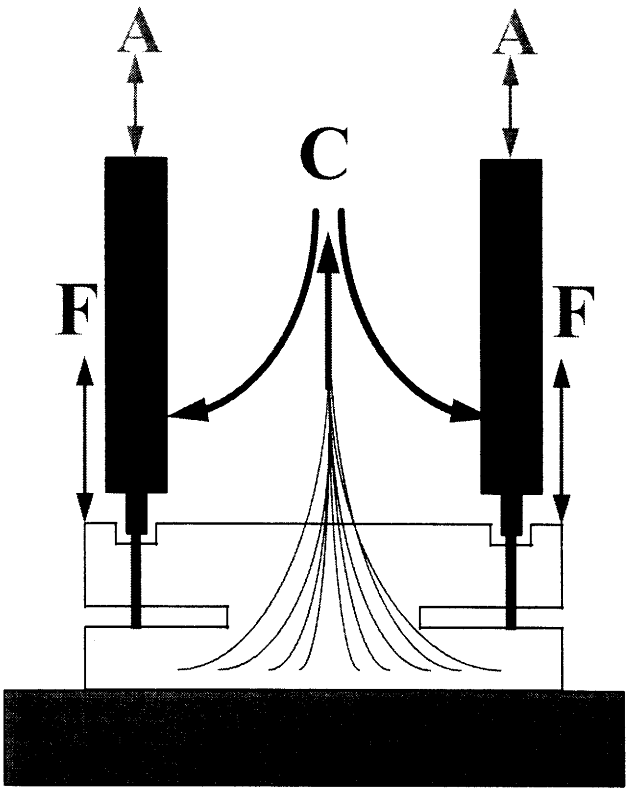


Figure 3-2. Schematic of CLL lap process.

The CLL process requires the addition of two actuators (A) such that left and right tool bar position can be altered during lap processing. As before, computer analysis of the resistance across the row dictates the pneumatic force for taper control and process completion. In addition, computer algorithms control the stroke, or elongation, of the left and right actuators during the lap process. This closed-loop control system allows for throat height flatness adjustment across the slider row during lap processing, which results in reduced variance.

ELG Sample Size Increase

Originally, the CLL process was characterized with fewer resistor pair positions. The number of resistor sites was nearly doubled based upon end-of-line data analysis [86,87]. End-of-line variance is reduced with larger in-line sample size because the fraction of heads with measured (rather than extrapolated or interpolated) throat height increases. The improvement of end-of-line data variability was significant, as discussed in chapter 5. The cost associated with the resistor pair increase was a decrease in operator productivity, on a unit volume basis, and an increase in the unit capital cost due to additional wire bonding equipment.

Lap Component Redesign

Several of the lap components required major changes in order to accomplish the closed loop CLL process. The module block required the largest change due to the inclusion of left and right actuators.

Module Block Re-design

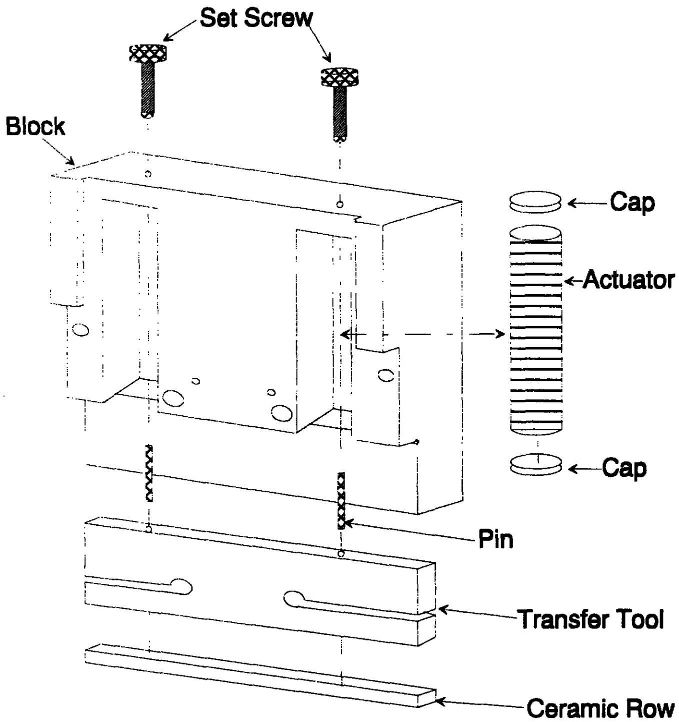


Figure 3-3. Closed-loop lapping module block.

The main components of the CLL module block are the actuation devices, transfer pins, electrical connectors (not shown), and two covers (not shown). The actuators fit into the left and right block cavities and provide the force needed to deflect the left and right "beams" of the transfer tool. The caps protect the actuator mechanically. The set screw provides an operator course adjustment at Row Bow.

Pin Redesign

The pin is used to transfer force caused by actuator elongation to the moment arm on the tool. The pins are inserted in the standard process set screw holes. The original pins did not have a head. The head addition incrementally improved linkage loss. Originally, the linkage loss was theorized to be one of the highest causes of "max out", i.e. reaching of actuator maximum position without the desired tool bar position being reached.

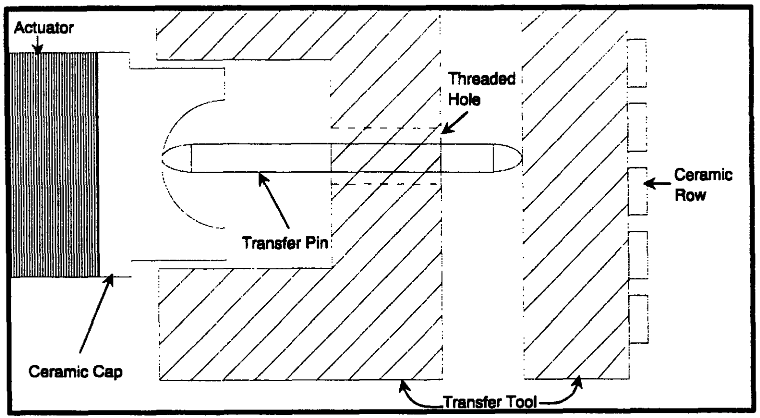


Figure 3-4. Ceramic cap and pin interaction with good alignment.

A pin with good alignment (Figure 3-4) rests at the bottom of the cup. A pin that was not positioned at the base of the ceramic cup (Figure 3-5) would "walk out" to the base during processing.

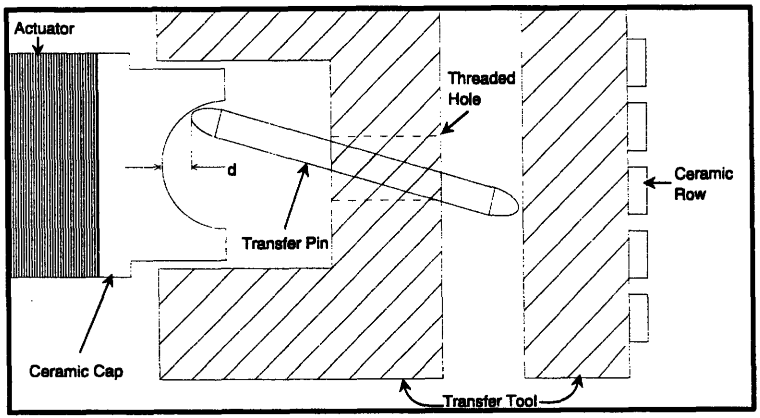


Figure 3-5. Cup/cone effect with offset 'd'.

Since dimension d greatly exceeds the maximum elongation of the actuator, the process could never recover and would "max out" with the row grossly out-of-flat. This would result in high process variability and high yield loss.

A methodology of minimizing linkage type losses was to minimize the number of interfaces. This was done with the future 3-point full redesign project, but could not be done with the current 2-point CLL process. An intermediate solution was the incorporation of a head onto the pin as shown in Figure 3-6.

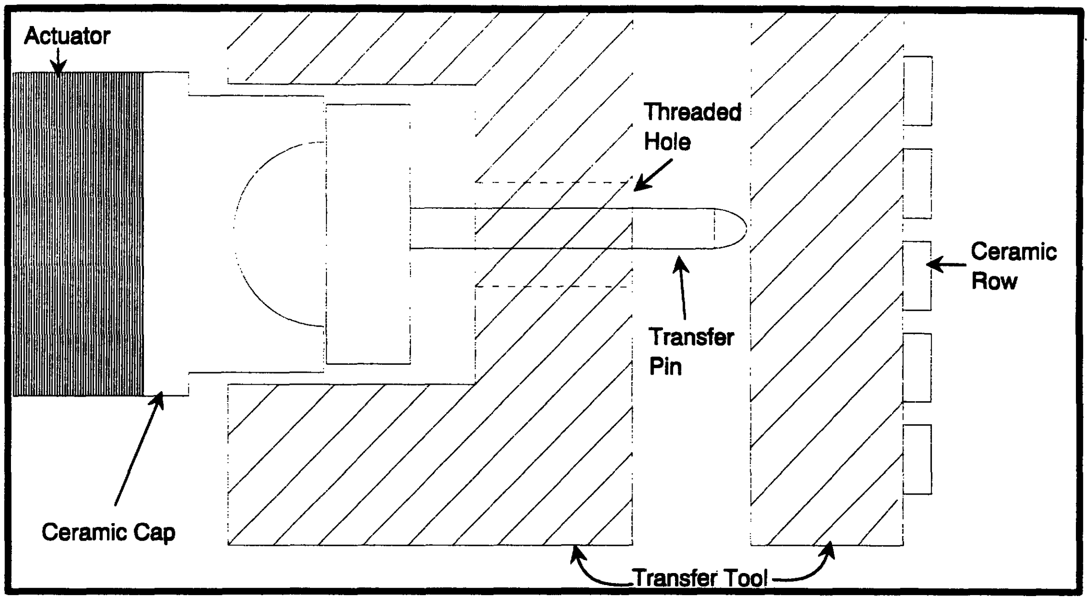


Figure 3-6. Transfer pin with head showing minimization of cup/cone issue.

A longer term solution was to replace the cupped ceramic cap with a flat cap, and use a cone type pin against this flat surface. Logistics of replacing several thousand caps negated this solution.

Cover Redesign

The module block cover is currently in re-design. Issues include transfer tool hold, operator ease of use, flex-print damage, and cavity hermetic protection. Design changes are based upon iterative machining, lap experimentation, data analysis and re-design PDCA cycles.

Modification of Transfer Tool

The transfer tool was slightly modified for the two-point CLL process. The spring constant of the tool was decreased by increasing the length of the left and right beams. The decrease in the spring constant was necessary as stroke of the actuator is linearly decreased by an increase in the applied force. Too small of an applied force is also a problem, as mechanical linkage problems occur. Components involved in the mechanical linkage error include two ceramic end caps, electrostrictive actuator, set screw, transfer pin, and transfer tool. Finite element analysis was done on the current modified CLL tool.

The pre-bow of the transfer tools has also been modified for the CLL process. Pre-bow is the amount of negative bow built into the tool in its free standing state. A negative bow is necessary in order for the tool to back-off past zero flatness when needed. Issues that require this back-off include cut flatness in the row saw operation and glue line problems.

Electrostrictive Actuation

Actuator Displacement and Resistance Characterization

Actuator electrical and mechanical characterization techniques were developed in-house with the aid of the actuator vendor. Mechanical displacement stations were built for both single actuator analysis and module block actuator analysis. Various standard electrical characterization tools were used based upon actuator characterization literature and discussions with the actuator vendor.

The purpose of the actuator characterization stations is the quantification of physical displacement, or stroke, when a voltage is applied. Actuators were characterized for vendor quality analysis, process fault isolation, encapsulation process analysis, and new tool design analysis. The single actuator station (Figure 3-7) uses an I-Beam for deflection and application of force while the dual actuator module block station (Figure 3-8) uses a standard transfer tool for applying force and measuring deflection.

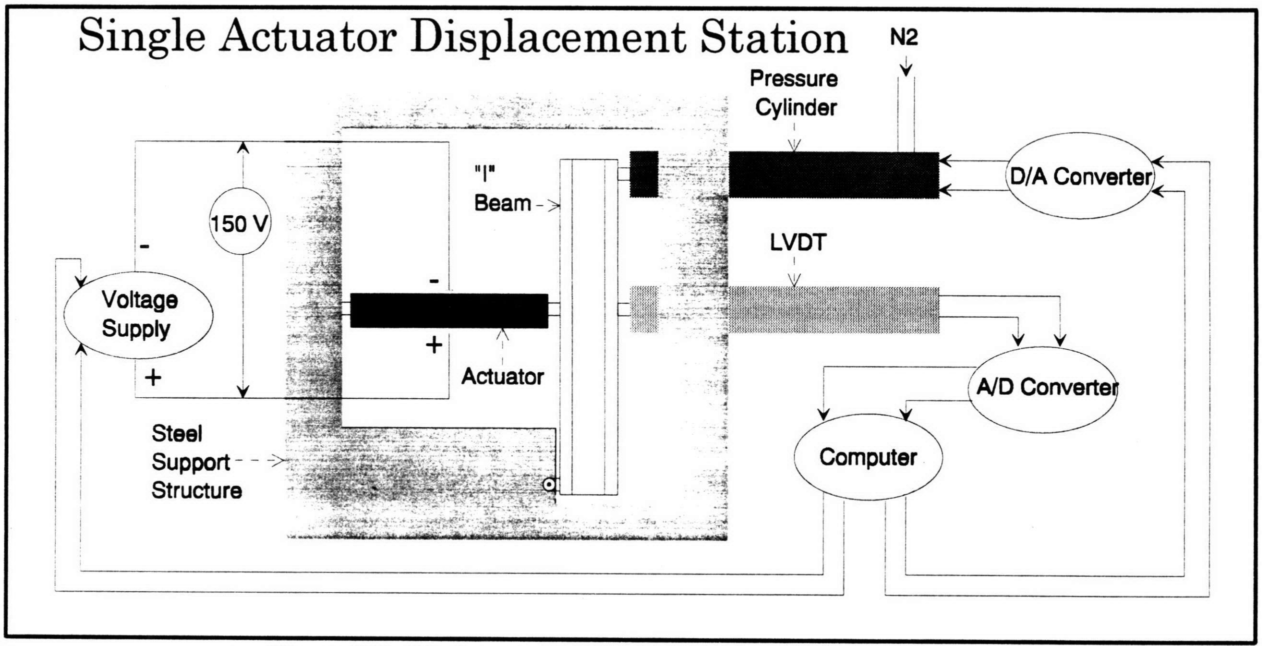


Figure 3-7. Single actuator displacement vs. voltage analysis station.

The test station consists of a LVDT (Linear Variable Displacement Transducer) for accurate displacement measurement, a standard digital multimeter for voltage monitoring, a computer for data analysis, a pressure cylinder for the variation of force, a custom-built voltage supply, and a steel support structure. A hinged 'I' beam was used for the application of force while providing a stable structure for displacement monitoring. The station is presently not able to control the voltage supply nor the D/A converter as would be desired for extended cycle actuator analysis.

The module block actuation station [Figure 3-8] uses three LVDTs for deflection analysis on the left, center, and right sides of a tool. This station was the foundation for actuator/tool/module block/pin interaction characterizations as well as new triple point tool and block analysis. The station could also be used for actuator charge loss[i] analysis, though electrical characterization methods were preferred. Similar to the single actuator station, extended cycle analysis could not be completed due to the lack of an automated voltage controller.

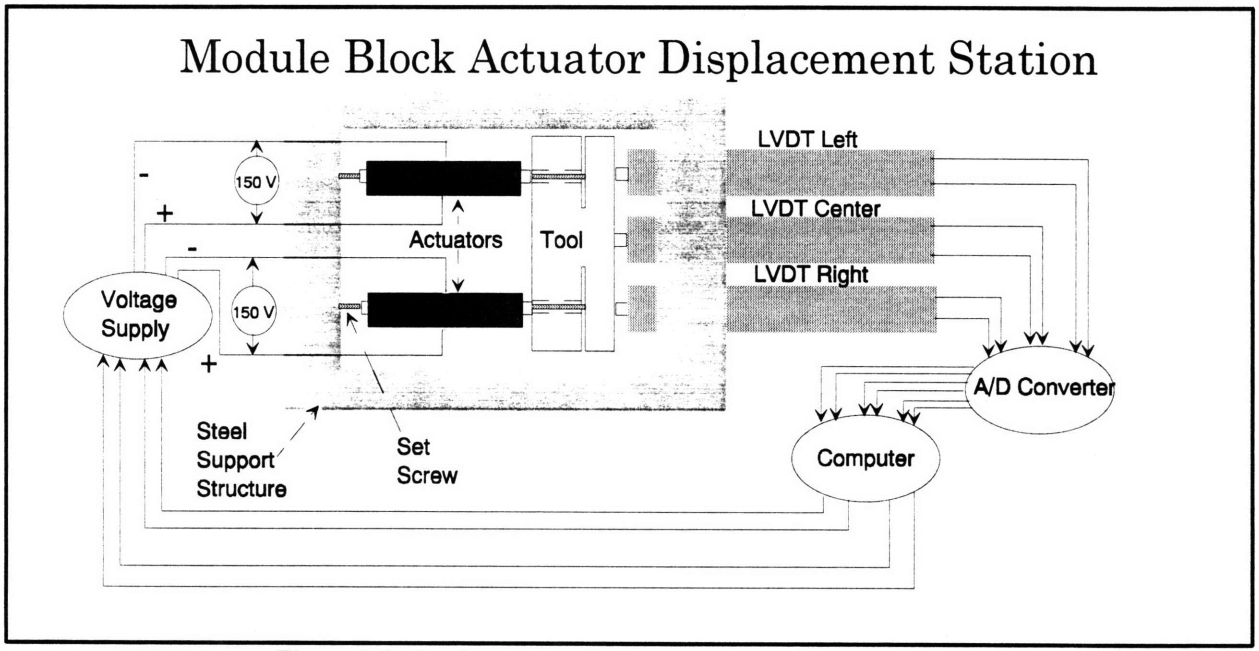


Figure 3-8. Dual actuator displacement vs. voltage analysis station.

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[i] Actuator charge loss is the loss of a voltage potential across the dielectric after the actuator is removed from a power source. This is usually caused by dielectric breakdown (cracks in the ceramic), or by shorting of the electrical connections.

Electrical resistance of the multi-stack actuator was measured with a megohmmeter. Electrically, the actuator behaves like a capacitor rather than a resistor. High resistance testing was not precise but it was valid for the type of go/no go binning required in fault isolation analysis. A "good" actuator with minimal leakage would have resistance >250 M ohms, while a leaky actuator would usually have resistance of less than 1 M ohm [60].

Encapsulation Process

Charge-loss was encountered during the pilot-line phase of the CLL process development. Actuators were partially coated with a hermetic polyurethane[ii]. Engineering analysis revealed that actuators were intermittently exposed to water in an operator cleaning process. The water would enter the actuator cavity and either cause higher leakage current or full discharge, dependent upon the amount of water and the condition of the actuator with regard to internal dielectric cracks. The charge loss would result in poor ramp metrics as the actuator could not maintain its final voltage. In order to improve upon this mode of CLL failure, an extensive amount of work was performed by the team on selecting a potting material and perfecting the encapsulation process.

Mold materials and designs were improved upon with an iterative PDCA method until a suitable solution was found for medium volume production [Figure 3-9]. Teflon was selected as the material for the multiple-cavity mold - its relatively high cost was negated by its good part release characteristics, even when spray mold release wasn't used. An internal machine shop provided very quick turn around on new mold designs, allowing several design iterations each week.[iii]

[ii] This hermetic polyurethane was commonly used on 5 volt PC boards while the voltage applied to these actuators was 0 to 150 volts.

[iii] A top cover was not used in the final design - this provided a smoother actuator surface and an easier manufacturing process.

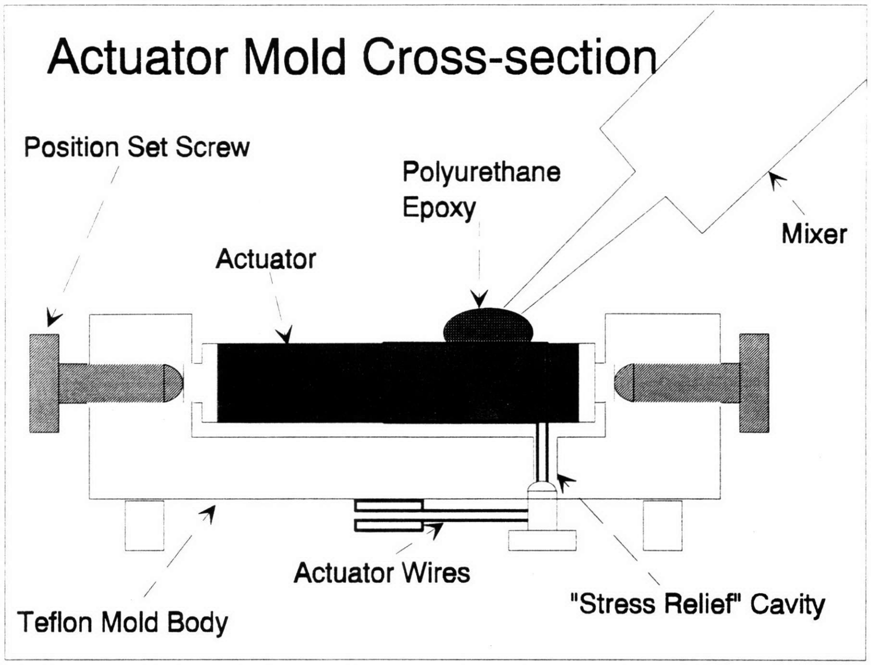


Figure 3-9. Teflon cavity used to mold polyurethane around the actuator.

The encapsulant provided stress relief for the wires in addition to providing enhanced hermeticity. The stress relief was vital for hermetic as well as electrical performance under the given operating conditions.

Several different styles of potting polymers were examined with none of the materials resolving all issues. The manufacturing process of actuator potting was improved with standard Deming PDCA cycles, with much of the improvement involving operator suggestions.

Data Driven Decisions - Enhanced Information Technology

Database Redefinition

Early in the internship the Slider database was recognized to be insufficient with regard to type of information collected and sample frequency. Upon agreement with several content experts, the database was extended and automated. The database enhancement was fortuitous as data driven decisions became more prevalent.

Data Analysis Software Programming

The purpose of writing analysis routines was to provide diffusion of CLL technology metrics during the implementation and production phases of the CLL project. A secondary purpose was to demonstrate how information technology can assist process engineering in early problem detection and capability analysis.

Tables

Summary tables were calculated on a weekly basis for both CLL and standard lap processing. Summary tables include analysis of the primary metrics of lap yield, lap throat height standard deviation, and ramp yield. These primary metrics are broken out by product, lap machine, and production shift. Loss codes are scrutinized to indicate dominant failure modes. A quality factor is calculated for "within group" quality comparisons. This factor is a function of lap yield, lap standard deviation and ramp yields.

Graphs

Shift analysis tables of secondary metrics are generated for both CLL and standard ELG processes. Bar graphs are easily created from any of these tables to visually enhance problem communication to engineers, technicians and operators. Bar graphs are created for the primary metrics while trend graphs are generated for the primary CLL metrics. These graphs are made more useful when annotation of process changes (hardware and software) are included on the graphs. Probability plots are generated with data analysis software. Probability distributions from various sources can easily be overlayed, and differences understood. These graphs are fundamental for quick problem analysis and resolution.

Probability plots are automatically created for the following:

Lap Standard Deviation of all Lap Machines
Lap Yields
Ramp Yields
Lap Over Lap Losses
Lap Under Lap Losses
Lap Bad Resistor Losses
CLL Standard Deviation of all Module Blocks
CLL Yield of all Module Blocks
CLL Ramp Yield of all Module Blocks

Plots are automatically generated with statistical capability analysis software routines. Specification limits can be changed in the future, as the process is under continuous improvement. Cpk distribution analysis is not valid for these values as the specifications are not real. The usefulness of the capability graphs lies in the fact that engineers on this site are more familiar with these graphs than probability graphs, and skewed populations can be easily identified.

Capability graphs are automatically generated for the following:

Total CLL Population Ramp Yield
Total CLL Population Lap Yield
Total CLL Population Lap Standard Deviation
Total Standard Population Ramp Yield
Total Standard Population Lap Yield
Total CLL Standard Lap Standard Deviation
CLL Left Actuator Final DDT Value
CLL Right Actuator Final DDT Value

The actuator Displacement Distribution Technique (DDT) capability graphs are vital for the understanding of CLL process capability. "Min outs" are a dominant process/equipment failure mode and during full scale manufacturing. "Min outs" are due to lack of process deflection capability on the low end. The control loop attempts to "pull back" the beam by lowering the voltage applied to the actuator; when the voltage is at its lowest level the beam deflection is at a minimum.

Any sufficiently advanced technology is indistinguishable from magic.
Arthur C. Clarke

Chapter 4: System Dynamics Modeling of the Lap Process

Vensim™ software [100,101] was used to model all primary physical interactions occurring in the Closed Loop Lapping (CLL) module block. This model simulates a process of actuator pre-charge (150 volts), row flatness pre-adjust (700 u"), row bow adjustment (+400 u"), lap voltage change (decrease to 60 volts and sine wave modulation), and lap variance change (due to linkage slip). The model indicates that an increase in the tool pre-flatness is vital to obtaining a robust ceramic lap process. Changes in tool width, cut height, and cut length are also simulated.

Vensim™ Model Description

Vensim™ is a systems dynamics software simulation tool. Its power lies in its ability to analyze a problem both conceptually and mathematically. The conceptual analysis is primarily iterative causal loop generation and refinement. It is during this portion of the model building that cause and effect need to be understood for each element of the model. The mathematical simulation ability allows "what if" type analysis to be performed. This leads to problem insight above and beyond what the model maker had before the problem analysis.

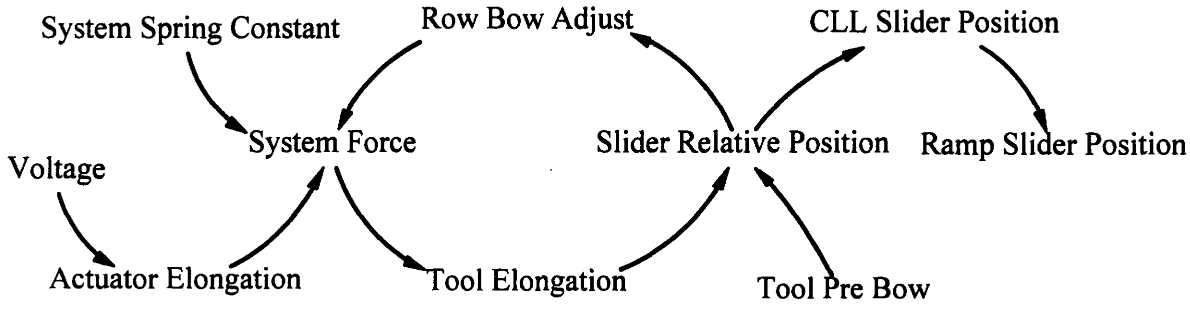


Figure 4-1. Primary variables of the CLL actuator/module block system.

A simplified version of the Vensim™ module block stroke model is shown in Figure 4-1 and the full model is shown in Figure 4-2. Each variable is defined mathematically such that the model produces a final tool position value. Units are defined for each variable and must pass an error check before the simulation can run. Attachment 1 describes each variable in detail.

The model is structured to represent the various phases of the Closed Loop Lapping process. Each section of the model represents either process or equipment functionality. The large arrows in Figure 4-2 indicate the "flow" of the model from *Computer Voltage Ramping* to *Ramp Slider Position.*

Any of the variables may be altered for "what if" type analysis, but the primary "what if" variables used in this analysis are marked by the diamonds. Variable interactions are specified in detail in the model description sections later in this chapter.

Each variable represents either a lap processing procedure or an engineering metric that can be altered and analyzed. Simulation of *tool width*, *cut length*, and *cut depth* are completed in order to understand the impact to final CLL process range and provide insight into a tool geometry factorial design of experiments. Similarly, the *Row Bow Preset Start Value* and *Desired Slider Target Position* are altered to investigate their impact on ELG process range. *Linkage Loss* is simulated in order to analyze its negative impact on process capability. *Broken Actuator* simulates stroke loss if one of the two actuators is broken. The various voltage loss variables simulate charge depletion during different parts of the slider lapping process.

Slider Position Module Block Stroke Model

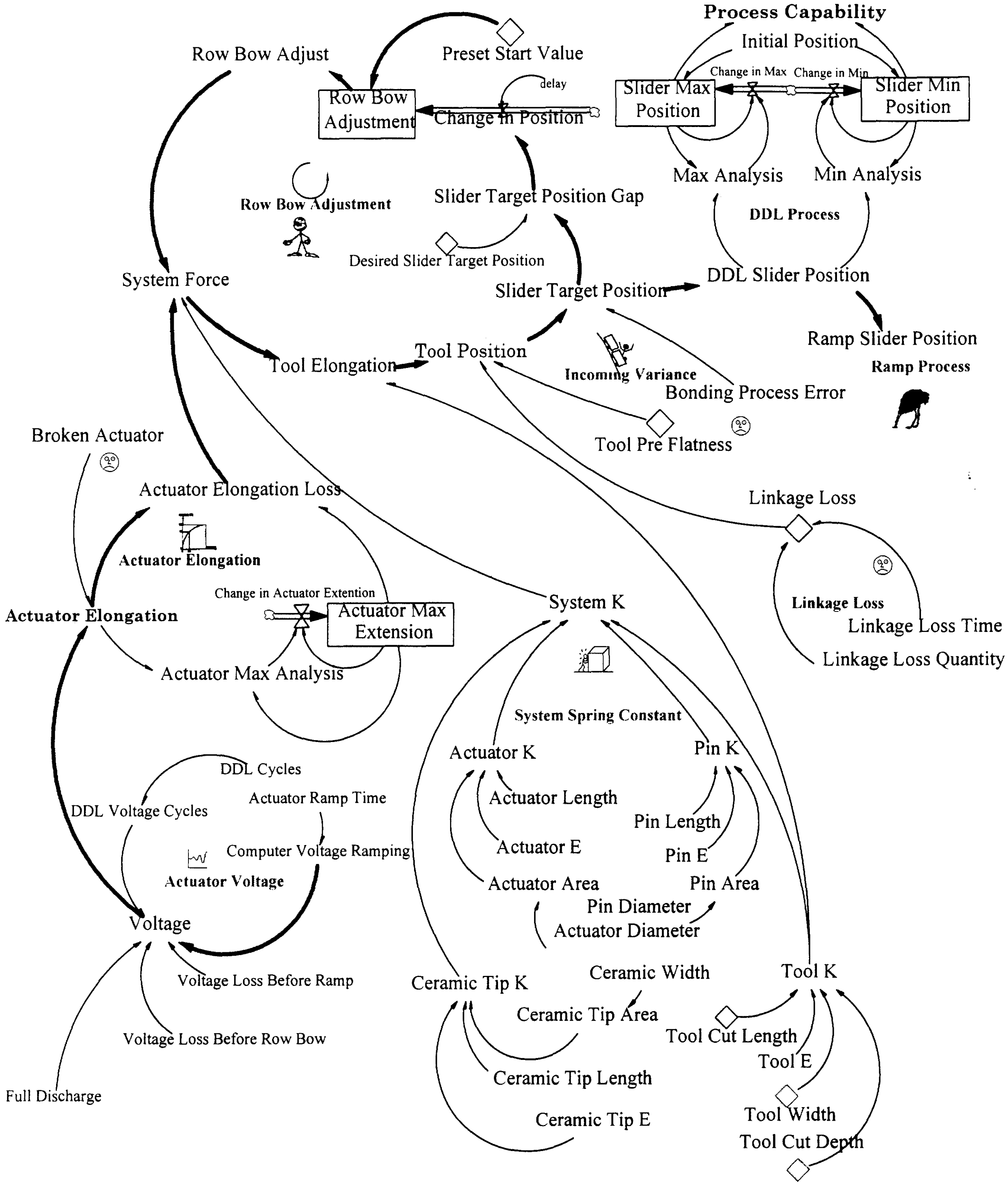


Figure 4-2. Actuator/module block process system model.

The core metric of the analysis model is slider Z position as a function of process flow. The slider position is eminently dependent on tool deflection, as described in chapter 3, but also on slider bar bond divergence. The tool deflection is dependent on the calculated spring constant of the entire module block system, which in turn is contingent on the spring constant of each individual component. Actuator length is dependent on voltage applied, with 150 volts representing full actuator stroke. Actuator stroke is at a minimum at 15 volts due to lapper hardware limitations.

The *Row Bow adjustment* modeling is iterative; this is similar to the actual operator row bow procedure. The operator adjust the tool deflection to a given value, measures the bar bow with an optical measurement tool, and adjusts tool deflection with set screw adjustments. The *desired tool position* is the row bow adjustment target (400 +/- 50 u"). The *preset start value* or operator row bow pre-adjust is the amount of deflection the operator applies to the tool bar before the initial Row Bow measurement.

Description of Graphs

The graphs that the model creates show cycle (x axis) versus variable value (y axis) as shown in Figure 4-3. The first 45 cycles represent the charging of an actuator to 150 volts. This does not impact slider position (set screws are backed out), and the slider position is equal to the *Tool Pre Flatness* value (-400 u"). Operator pre-adjust (700 u") occurs at 50 cycles, along with the start of the row bow process.

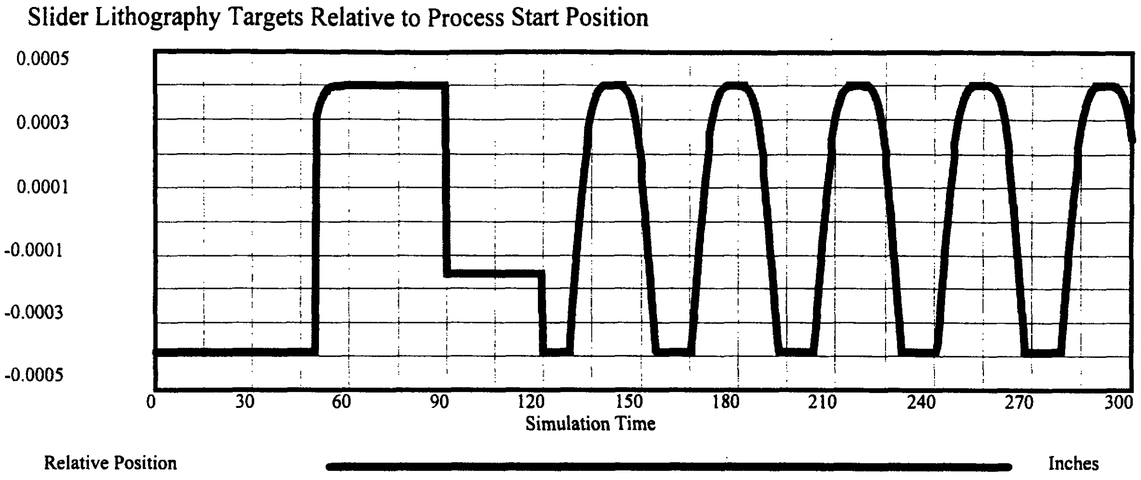


Figure 4-3. Slider target relative position vs. cycle number.

The iterative Row Bow reinforcing loop adjusts the tool position to reach the *Desired Slider Target Position* of +400 u". At 90 cycles the module block is placed in the lapper, and the voltage is decreased to 58 volts (i.e. brings the slider position from +400 u" to 0 u"). At 120 cycles a CLL process is simulated with 5 major sine waves varying the voltage from maximum (150 V) to minimum (15 volts). Linkage loss is simulated at 150 cycles (when it is turned on). Actuator breakage can be turned on at any cycle.

Actuator stroke as a function of process flow is modeled with cycle time in Figure 4-4. Initially the actuator is at zero stroke. The voltage is then ramped to 150 volts in 30 cycles, producing 1600 u" of deflection. The voltage is held at 150 volts until the 75th cycle when it is lowered to 60 volts, or 1000 u" of dual stake actuator elongation. At 120 cycles the elongation follows the voltage sine wave and modulates deflection between 300 and 1600 u", which represents CLL processing. Actuator elongation length (or stroke) changes non-linearly with applied voltage due to electrostrictive properties discussed in chapter 3.

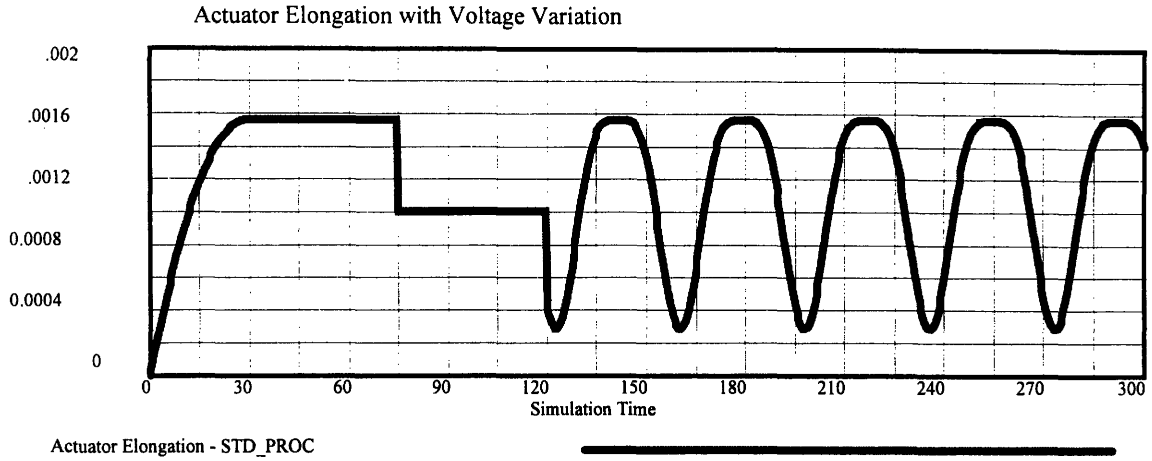


Figure 4-4. Actuator elongation length vs. cycle number.

The simulation software allows random number generation as variable input. This feature can be used to simulate true process variation around each variable, and thus examine total system impact and variable interaction. An example of this is shown in Figure 4-5 with voltage skewed random normal about 67.5 volts. The random number feature generates distributions that are normal, Poisson, exponential, gamma, pulsed and ramped. Random normal was selected because the current process exhibits a near normal distribution with a lower skew.

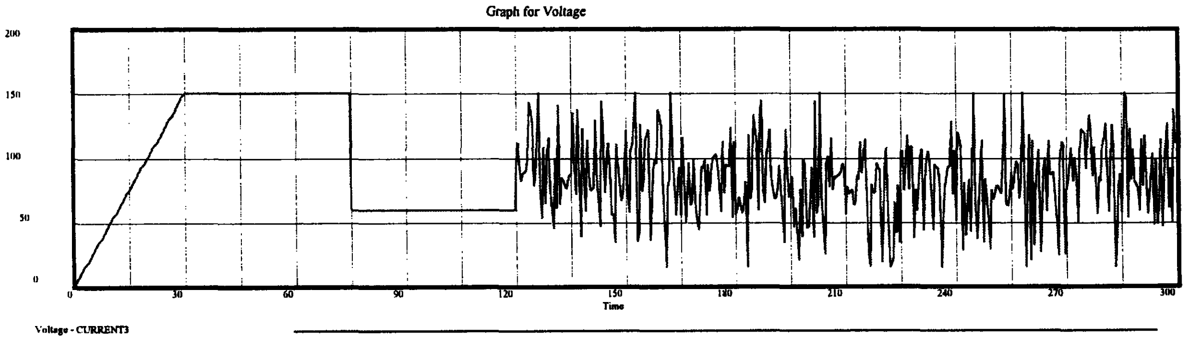


Figure 4-5. Actuator voltage during initial ramp, hold, decrease, and random during CLL processing.

Model Section Descriptions

Each of the model sub-systems are discussed in greater detail so as to facilitate deeper understanding of the model as a whole, and also to provide examples of various CLL process interaction effects.

Tool Bar Spring Constant

A fundamental assumption of the model is that each half of the tool bar behaves mechanically like a beam attached to a wall. The deflection of the beam is dependent upon the length, width, depth (or thickness), and modulus of elasticity of the beam.

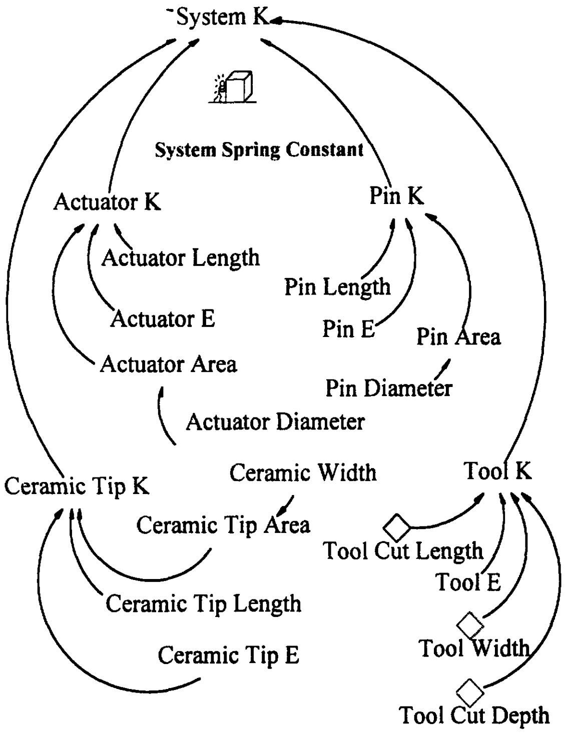


Figure 4-6. Spring constant model sector.

The beam length is determined by the length of the tool bar cut. The cut length is longer on CLL tools than on standard tools; a lower force was needed for use with the electrostrictive actuators because deflection was below a desired range. Tool bar width and modulus of elasticity is identical for both processes, but tool cut depth is lower on CLL tools to facilitate enhanced actuator extension.

The "system" spring constant is calculated from the spring constants of the individual components as shown in Figure 4-7. The system represents one-half of the module (left/right) and is composed of an actuator, two ceramic caps, a transfer pin, and the transfer tool.

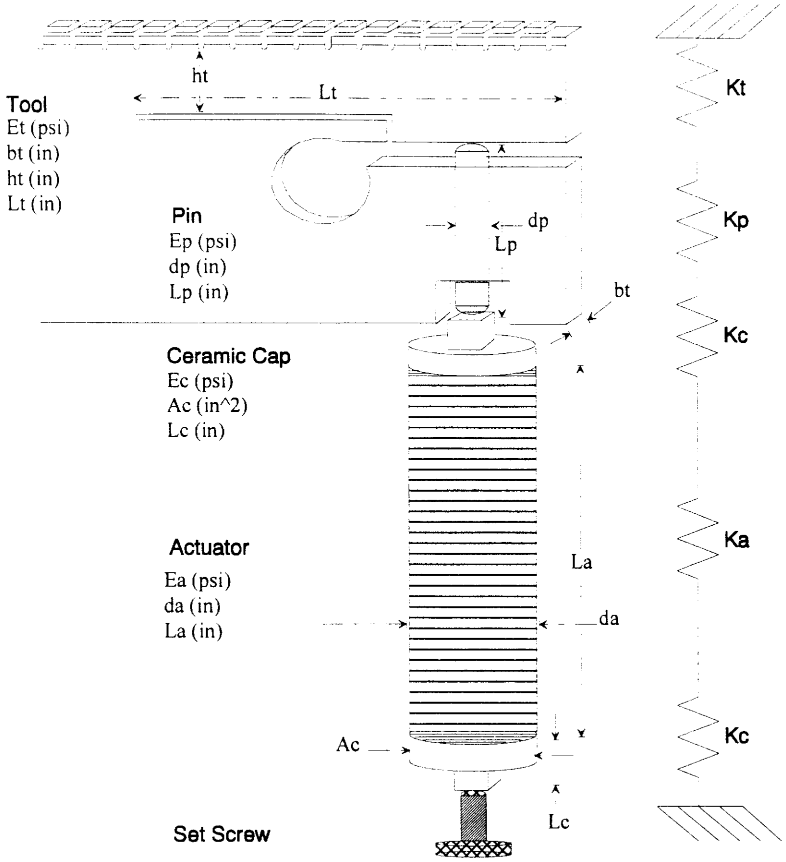


Figure 4-7. System spring constant components.

$$K_t = 3E_t \frac{I}{L^3} = \frac{E_t \cdot b_t \cdot h_t^3}{4 \cdot L_t^3}$$

Equation 4-1. Tool "beam" spring constant.

$$K_p = E_p \frac{A_p}{L_p} = \frac{E_p \cdot \pi \cdot \left(\frac{d}{2}\right)^2}{L_p}$$

Equation 4-2. Transfer pin spring constant

$$K_c = E_c \cdot \frac{A_c}{L_c}$$

Equation 4-3. Ceramic cap spring constant.

$$K_a = E_a \frac{A_a}{L_a} = \frac{E_a \cdot \pi \cdot \left(\frac{d_a}{2}\right)^2}{L_a}$$

Equation 4-4. Actuator spring constant.

Materials properties and dimensions were either supplied by the vendor, measured, or found in literature searches. The set screw was not included in the system due to initial calculations showing little influence on the overall system. The system spring constant is calculated as follows:

$$K_{sys} = 1 \Big/ \left(\frac{1}{K_a} + \frac{1}{K_p} + \frac{1}{K_t} + \frac{2}{K_c} \right) = 2.72E4 \text{ lbs/in}$$

Equation 4-5. System spring constant.

Changes in *Tool Cut Length* directly impact the system spring constant, K_{sys} the system force, $F_{sys,}$ and the resulting *Tool Position* deflection. Figure 4-8 graphical displays the result of a 25% increase and decrease of cut length vs. nominal.

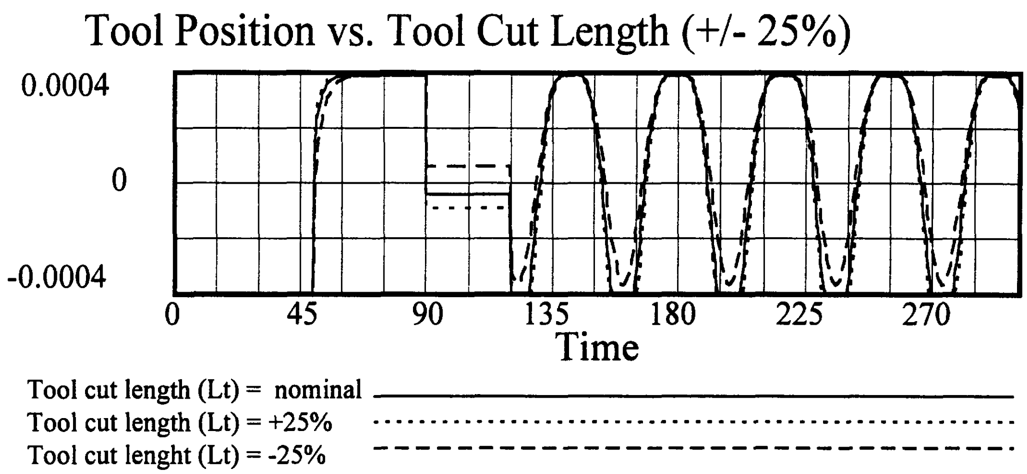


Figure 4-8. Transfer tool position vs. a 25% skew in tool cut length.

Note that the 25% decrease in cut length results in worse process capability. The system spring constant is much higher for a smaller beam, resulting in much higher system forces, and lower tool deflection capability. The resulting system forces are shown in Figure 4-9.

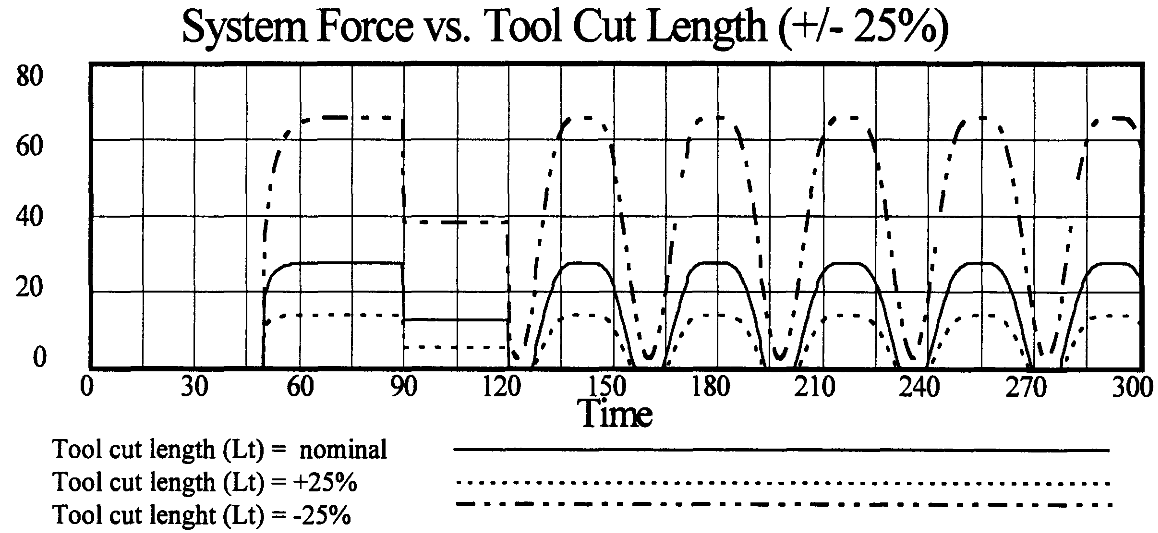


Figure 4-9. System force vs. a 25% skew in tool cut length

Tool cut length is the primary transfer tool metric that was analyzed with this model. The interaction of tool width and tool depth was analyzed because of lap stability concerns. If the tool "beam" twists the sliders on the end of the tool will have poor crown or surface flatness. One method of increasing the bar flex without significantly increasing twist is to increase bar thickness when the bar depth is decreased [Figure 4-10].

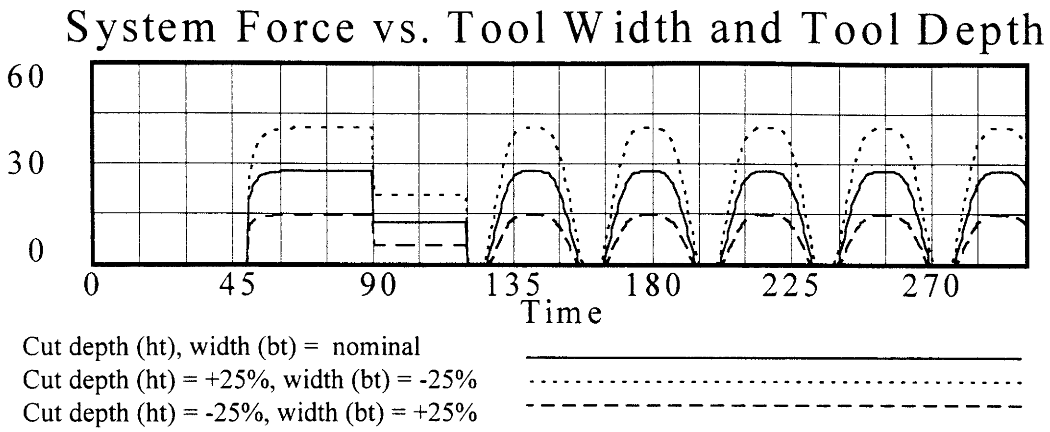


Figure 4-10. System force vs. simultaneous changes in tool depth and width.

As expected, the 25% increase in cut depth with a 25% decrease in tool width resulted in significantly higher required system force. The simulated decrease in cut depth with an increase in width resulted in much lower required system force. It was noted that one of the two external lap vendors applied this technique because of their use of voice coils (minimal available force).

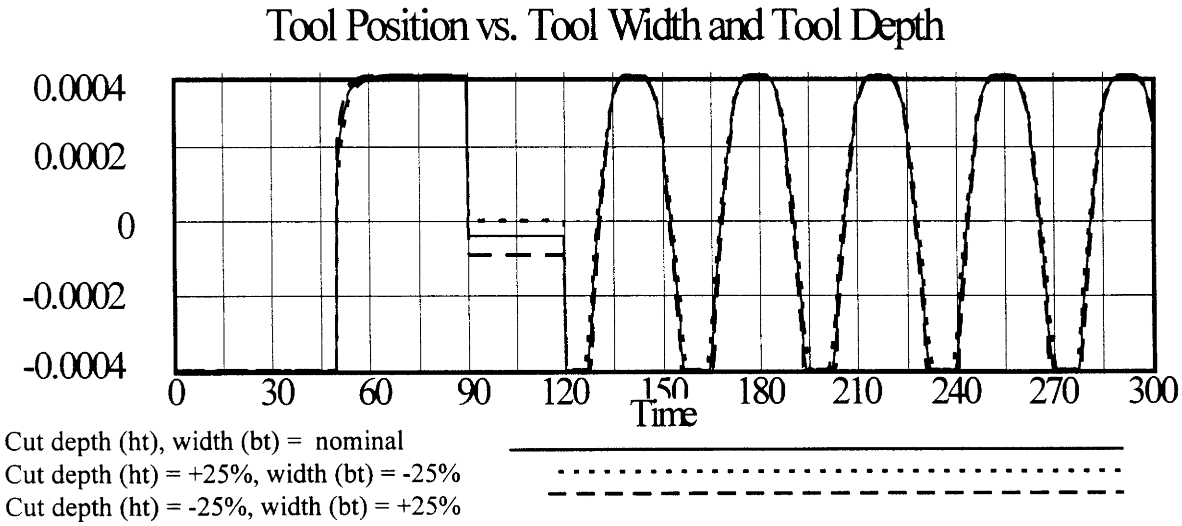


Figure 4-11. Tool position as a function of tool width and depth changes.

Actuator Elongation vs. Applied Voltage

The second fundamental sector models the interaction of the electrostrictive actuators and voltage. Key elements include empirical modeling of the electrostrictive effect, the impact of a broken actuator, and the impact of voltage loss during processing.

Actuator elongation vs. voltage was characterized with a no-load stroke measurement on several actuators. Polynomial regression fit the raw data to a line (Figure 4-13) which is used in the Vensim™ model. The second order relationship between voltage and displacement is due to the use of an electrostrictive material (chapter 3). Vendor characterization of actuator elongation yielded similar results.

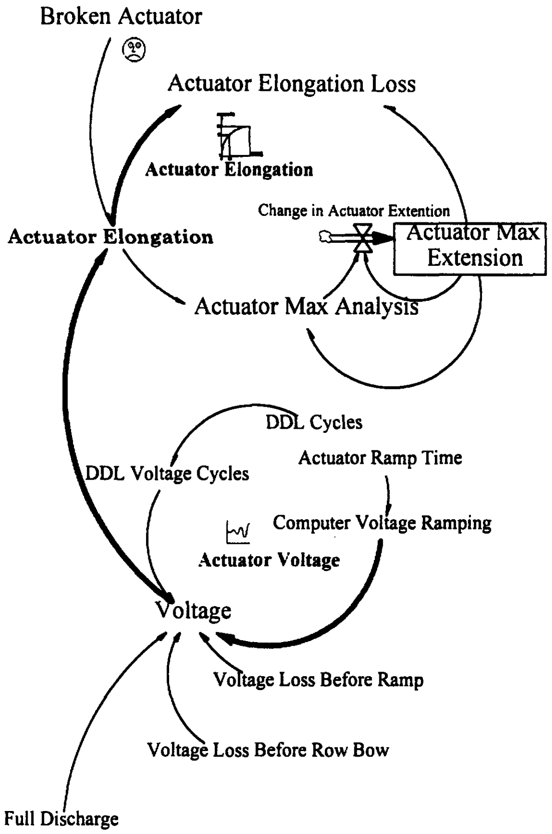


Figure 4-12. Actuator displacement vs. voltage

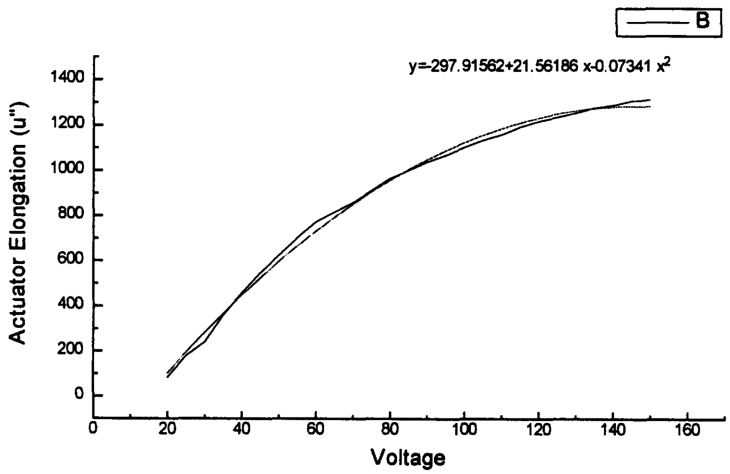


Figure 4-13. Measured actuator displacement vs. input voltage.

Actuator breakage significantly impacted process capability when the CLL process transitioned into full production. Several modes of operator induced actuator breakage were discovered and several engineering re-designs were completed during this time-frame. Figure 4-14 shows the impact a broken actuator has on the tool position while Figure 4-15 shows the impact on capability, as measured by maximum minus minimum tool position under full cycling.

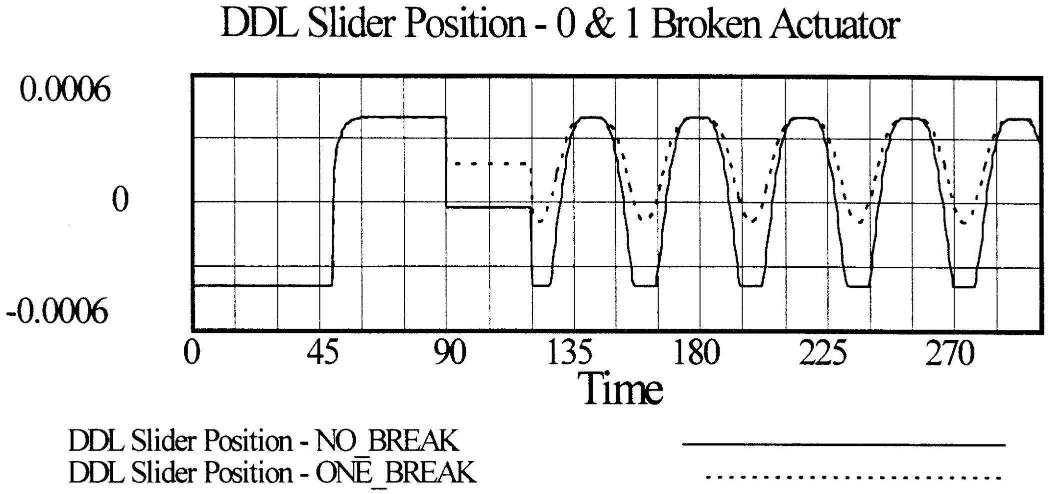


Figure 4-14. CLL slider position simulating a broken actuator.

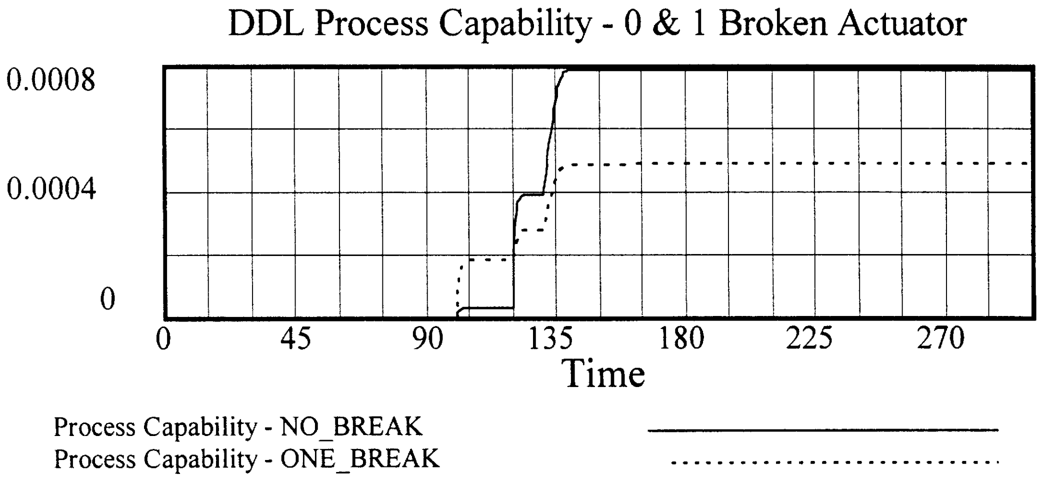


Figure 4-15. CLL process max - min tool deflection capability with a broken actuator.

Iterative Row Bow Adjustment

The Row Bow adjustment sector involves iteration until the *Slider Target Position* reaches a *Desired Slider Target Position* from a predetermined *Pre-set Start Value*. In the case of the December CLL process, the pre-set value was a 700 u" adjustment on a manual station prior to the first Row Bow reading.

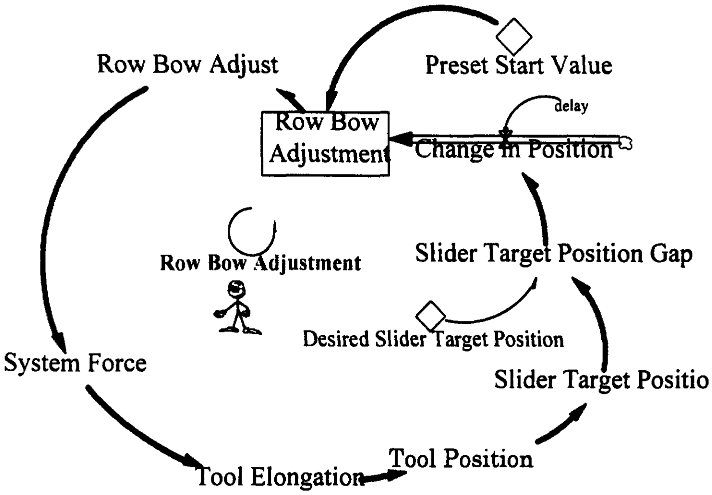


Figure 4-16. Row Bow adjustment loop

The *Desired Start Position* is set to 400 u" - this allows the bar to return to a flat state when the voltage is decreased from 150 volts to 60 volts. *Row Bow Adjustment* is a stock value, as per standard system dynamics technique when dealing with gap analysis [100,101].

The tool position or deflection is directly related to the applied system force as follows:

$$\sum F = 0 \therefore F_a = F_p = F_c = F_t = F_{sys}$$

Equation 4-6. Steady state body force analysis.

$$and \qquad F_{sys} = K_{sys} \cdot \delta_a$$

Equation 4-7. Deflection x spring constant = force.

$$so \qquad \delta_t = F_t / K_t = F_{sys} / K_t = \frac{K_{sys}}{K_t} \cdot \delta_a$$

Equation 4-8. Tool deflection as a function of spring constants and actuator deflection.

The model estimates that an actuator extension of 1200 u" will result in a tool deflection of 930 u" - this is close to actual measurements on the engineering analysis station. The system force is calculated to be 32.6 lbs for the baseline tool bar dimensions and material properties. A lower force is desired for enhancing actuator elongation, but this results in increased linkage losses.

Variance and Linkage Loss

Incoming and in-line variance have large negative impacts on the CLL process. Incoming slider position variance may be caused by operator bonding processing errors or just from poor process capability. Pre-tool flatness variance is not fully understood; plastic deformation of the stainless steel parts is possible but unlikely. Surface defects or burrs may play a role in the variance, but this has not been quantified.

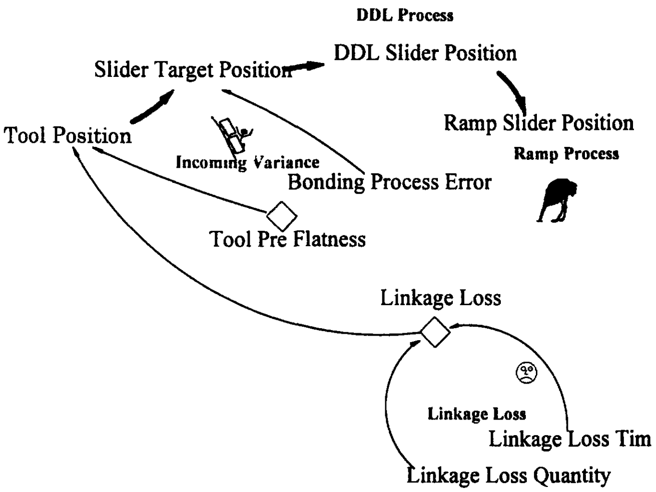


Figure 4-17. Variance and linkage loss sector.

The main source of linkage loss appears to be cup/cone interactions, as described in chapter 4. The sector simulates the cup/cone displacement loss as a set number, in micro-inches. The value *Linkage Loss Time* enables the linkage loss number to be turned on at a specific CLL cycle.

As described in Chapters 3, the author feels that a vital hardware change was the increase in the *Tool Pre-Flatness* from -400 u" to -1200 u". This change in built-in mechanical bow results in a much higher force on the mechanical linkages because the iterative Row Bow process is still required to hit the same desired target. The higher force should reduce linkage losses. The change also allows the process capability to be expanded, as the problem with process truncation is eliminated - note the sinusoidal shape of the -1200 u" pre-flatness tools versus the truncated sinusoidal shape of the -400 u" tools.

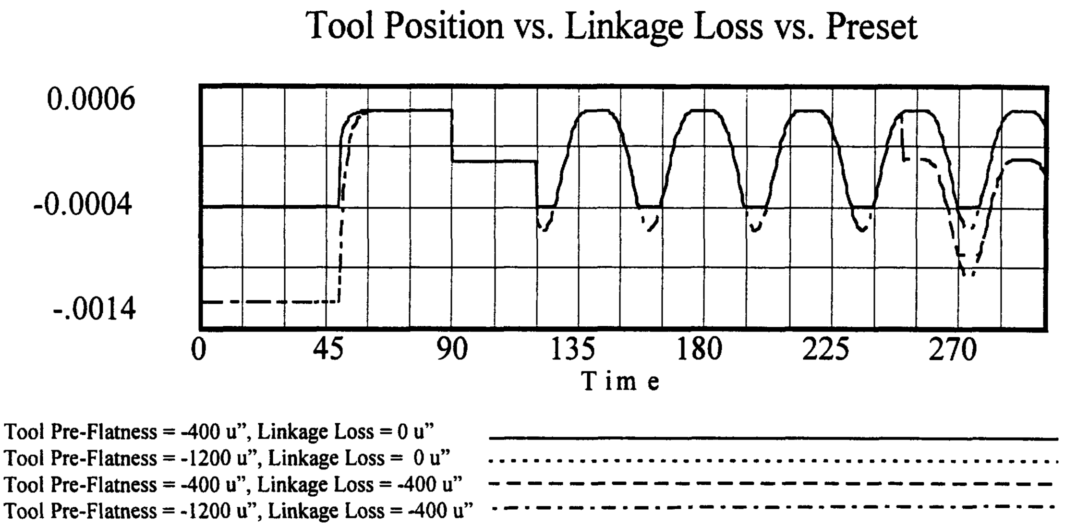


Figure 4-18. Tool position as a function of tool pre-flatness and linkage loss.

The linkage loss was turned on at cycle #250, resulting in the drop in tool position at that point. Note that the -1200 u" tool still maintains a sinusoidal distribution even with a 400 u" linkage loss. As of January 1996 the majority of the line was converted to -10/12 tools, meaning tools of pre-flatness of between -1000 and -1200 u".

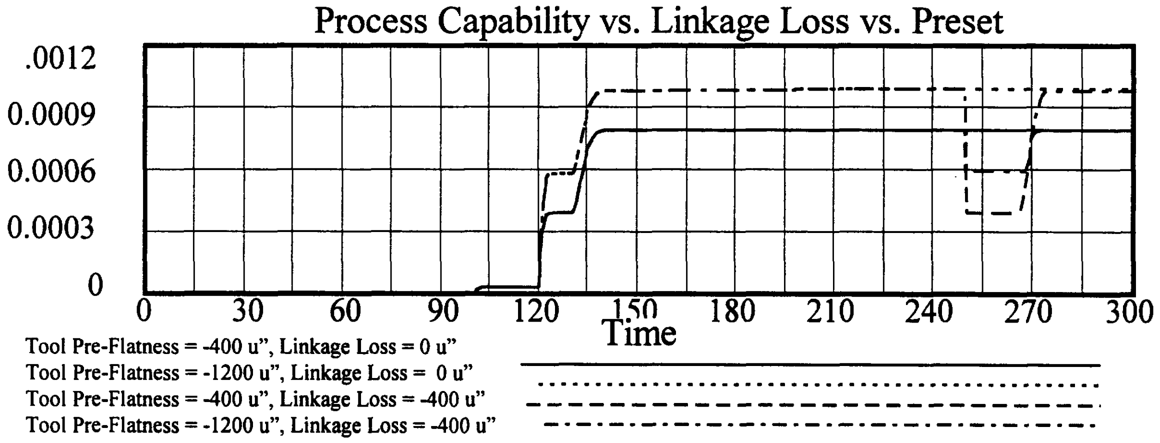


Figure 4-19. Process capability as a function of tool pre-flatness and linkage loss.

Process Capability

The last sector to be described is the process capability sector. The CLL DDT values discussed in chapter 5 are synonymous with this models *Process Capability* value.

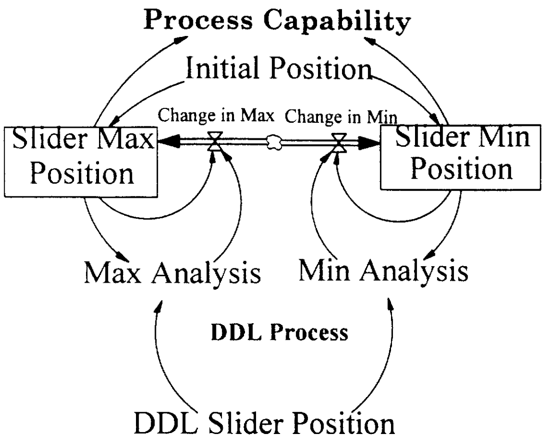


Figure 4-20. Process capability sector.

Both a minimum and maximum slider position "stock" needed to be quantified in order to calculate stroke capability. The stock values are contrasted with the slider position value for every cycle. If the slider position exceeds the Slider Max Position or is smaller than the Slider Min Position it will replace those values.

The process capability number is a useful metric because the true tool position range will determine CLL process capability. Figure 4-19 illustrates the models graphical output of process capability vs. linkage loss and tool pre-flatness. Figure 4-21 illustrates the modeled process capability of the standard process.

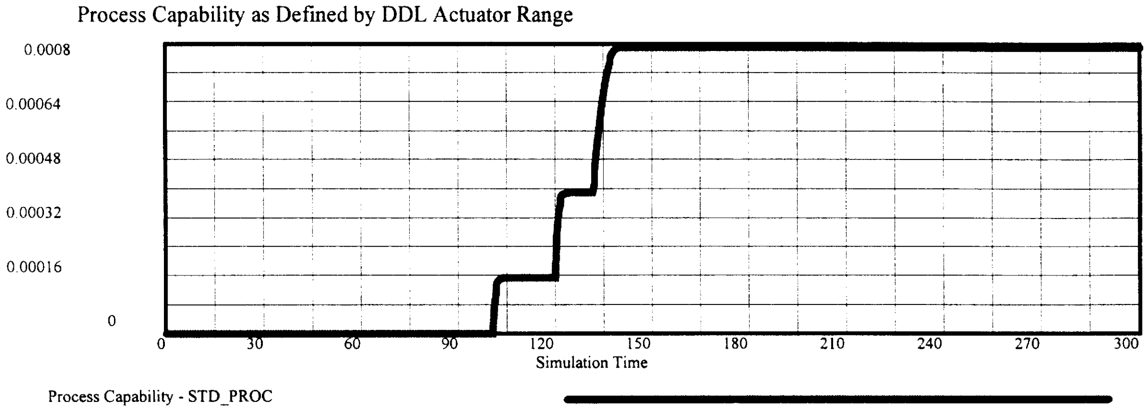


Figure 4-21. Process capability of the standard CLL process.

The reasonable man adapts himself to the world; the unreasonable man persists in trying to adapt the world to himself. Therefore all progress depends upon the unreasonable man.

George Bernard Shaw

Chapter 5: Results and Discussion

Electrostrictive Actuator Characterization

Electrical Impedance and Resistance

Published electrostrictive actuator characterization techniques [37] were used on several actuators to determine technique feasibility in a manufacturing environment. Electrical resistance versus frequency analysis correlated well with the vendor's results, but were not implemented due to technique cost and complexity. A secondary technique of high resistance capacitor analysis was recommended by the actuator vendor for technician or operator level electrical analysis - this technique was implemented and is currently being used in the module block preventative maintenance procedures. In this technique, low electrical resistance values indicate a problem with current leakage. Leakage sources have been isolated to poor connectors, cuts in wire insulation coatings, and cracking of the ceramic dielectric. Ceramic cracking is the most concerning cause, as the actuator can not be repaired.

Displacement

The single and dual actuator measurement stations quantified displacement vs. applied voltage for new and used actuators, as described in Chapter 3. The experimental displacement (micro inch or 10^{-6} inch) vs. applied voltage curve shown in Figure 5-1 deviates from the theoretical quadratic relationship at ~40 volts. Fripp, Hagood and Luoma [19] show that lead magnesium niobate/lead titanate (PMN-PT or $(0.9(Pb[Mg_{1/3}Nb_{2/3}]O_3\text{-}0.1(PbTiO_3)))$ displacement/voltage relationships deviate from standard models when the electric field exceeds 300 volts per millimeter of dielectric. A single 0.75" long electrostrictive actuator consists of ~150 layers, which translates into a dielectric thickness of ~0.12 mm. Thus the

Fripp 300 volt/mm electric field limit is reached at ~38 volts. The Hom and Shankar [29] displacement model for electrostrictive ceramic materials includes stress, strain, electric field, polarization and temperature variables, and closely matches the shape of the curve in Figure 5-1. In practice, deviation from this voltage/displacement function is an indicator of either a problematic actuator, voltage supply, electrical connection or module block.

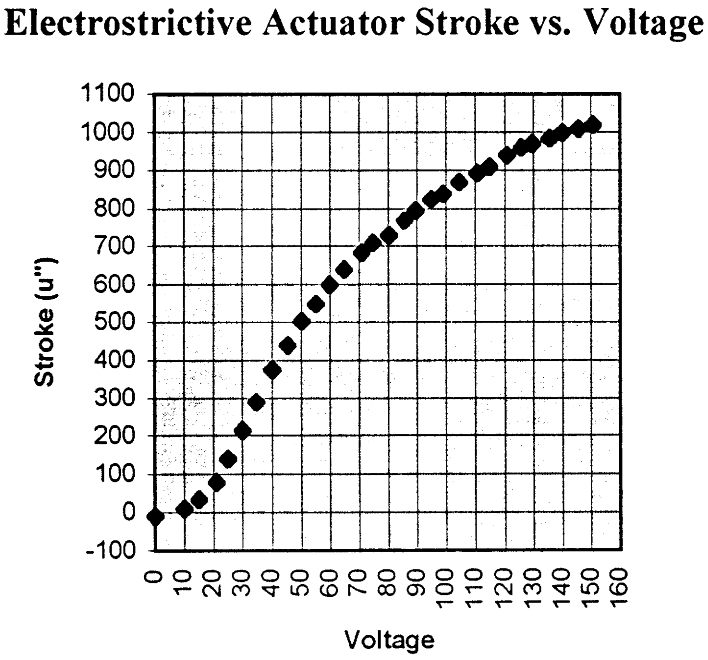


Figure 5-1. Measured displacement of electrostrictive actuator vs. voltage applied.

Cracking of actuators through either poor handling or misprocessing has been a major problem since CLL production implementation. A cracked actuator can exhibit either reduced elongation or no elongation, depending on crack severity. Stainless steel support structures have been incorporated into the potted actuator to minimize future actuator cracking.

The mechanical linkage of the actuator, transfer tool, pins and actuator caps can impact the displacement range of the system. Figure 5-2 indicates the reduction in system stroke as a function of pre-adjust or pre-set value.

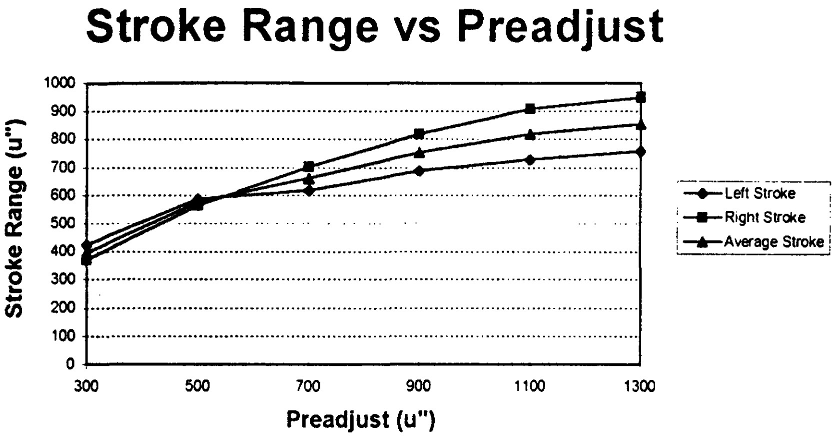


Figure 5-2. Actuator stroke range (max u" - min u") for various pre-adjustment values.

Larger pre-adjusts require larger tool bar beam bending, which requires higher forces to be applied against the beam. It is theorized that higher input force provides better mechanical linkage because of cup/cone self alignment.

As shown in the system dynamics modeling in chapter 4, a large stroke range is vital for obtaining high process capability. Poor stroke range will result in "min out" and "max out" scenarios where the control loop is limited by an actuator extension boundary condition. "Final DDT" capability analysis is a good indicator of actuator process robustness and is explored later in this chapter.

Reliability Issues

Five production worthy polyurethane potted actuators were tested with the 85/85 reliability test. This test is a hermetic acceleration reliability test at 85 degrees C and 85% relative humidity. The test conditions were repeated twice by the internal reliability group. All 5 actuators passed the success criteria of electrical isolation resistance and stroke hold pre/post accelerated water exposure. The results are as follows:

Table 5-1. Pre 85/85 Reliability Values

Actuator #	*Stroke (Time = 0)*	*Stroke (Time = 1 min)*	*Resistance (M Ohms)*
20	*980 u"*	*970 u"*	*275*
T1	*1295 u"*	*1300 u"*	*400*
T2	*1265 u"*	*1265 u"*	*350*
64	*1335 u"*	*1335 u"*	*500*
70	*1200 u"*	*1200 u"*	*275*

"Stroke" refers to full voltage (150 volts) elongation as measured with LVDTs on the actuator test station. "Stroke + 1" refers to stroke one minute after removal of a supply voltage. On bad units with cracks the stroke will rapidly drop several hundred microinches in one minute. The resistance was measured with a MegOhmmeter.

Table 5-2. Post 85/85 Reliability Values

Actuator #	*Stroke (Time = 0)*	*Stroke (Time = 1 min)*	*Resistance (M Ohms)*
20	*990 u"*	*990 u"*	*900*
T1	*1265 u"*	*1265 u"*	*800*
T2	*1275 u"*	*1275 u"*	*350*
64	*1305 u"*	*1305 u"*	*400*
70	*1120 u"*	*1120 u"*	*375*

Values above 150 Mohm indicate good electrical resistance - poor actuators have values of 1000 ohms to 1 M ohm, so the test can easily identify charge loss shorts. In addition, an actuator with a 4 day water immersion had good electrical results. Vendor specs of the specific polyurethane used in this potting are 0.7% water absorption in a 4 day period with full immersion. Other urethane and silicon potting materials had better water absorption properties but were difficult to use because of either limited cure times or safety issues. A thin polyisobutylene or butyl rubber coating over the polyurethane potting is currently being studied as a hermetic improvement. Close-packed linear paraffinic chains of these synthetic elastomers results in low water permeability [3, 79]. A secondary "fix" of the actuator charge loss problem is enhanced training of operators on the proper use and care of a module block.

A sample of the potted actuator was also sent to the actuator supplier for electrical and displacement analysis. The vendor preferred the potting material, the overall design and especially the new wire stress relief. Another sample was given to the corporate SEM/analytical lab for cross section analysis of the ceramic/polyurethane interface and elemental composition analysis.

Primary Engineering Metric

Throat height standard deviation is the primary quality metric used in ceramic slider manufacturing. As discussed in chapter 3, throat height is measured electrically in-line with the analog and digital resistors. End-of-line throat height is quantified either optically or with scanning electron microscopy (SEM) on physically polished cross-sections.

In-Line vs. End-of-Line Data Correlation

CLL electrical component height was characterized with in-line and end-of-line metrics. Quantification of end-of-line throat height variance versus the number of good resistor bonds establishes minimum bond requirements. 100% measurement of all of the row resistors is not feasible due to equipment limits and productivity impact, so only a limited resistor sample size is used on the standard lap process. Throat height is estimated for the remaining non-bonded sliders. It is not uncommon for the standard bond procedure to produce non-functional electrically continuous Rp/Rb pairs, as the bonding process is impacted by operator skill level, flex print quality and usage, bonder set-up, and surface contamination levels.

Experimental data indicates that reduction in in-line throat height variance produces significant yield improvements and higher part quality as measured by throat height variance. In order to quantify the electrical resistance correlation with physical throat height, cross-section analysis was performed on both engineering samples and random production samples. The ceramic sliders are mounted in epoxy, and lap polished to the electrical component mid-point. Throat height is determined with optical microscopy for inductive heads, and Scanning Electron Microscopy (SEM) for MR heads. Samples are then marked 'good' or 'bad' dependent upon processing history.

Throat height standard deviation and process capability (Cpk) was quantified vs. number of bonds, and by relative bond position on a tool bar. Note that the new bond process (NBP) nearly doubles the number of Rp/Rb pairs. End-of-line throat height variance increases as the number of bonds decreases, as expected. Throat height variance increases with an increase in the relative distance from a bond site (interpolation/extrapolation errors). End-of-line process capability (Cpk) is below 1.00 for all processes except the new bond process, thus making NBP the recommended process.

172 ceramic sliders from 10 lots of a high volume product were precision cross-sectioned with throat height optically quantified. Cross-section data was correlated with in-line electrical data. Of the 172 heads, 136 samples had passed all in-line engineering parameters and where thus considered 'good' material, as they would have passed the criteria for shipment to a customer. Bars had either N, N+1, or N+2 good bonds, where N represents the number of bonds in the standard process. An additional lot was processed with the new bond process and 10 "good" end-of-line cross-sections were obtained.

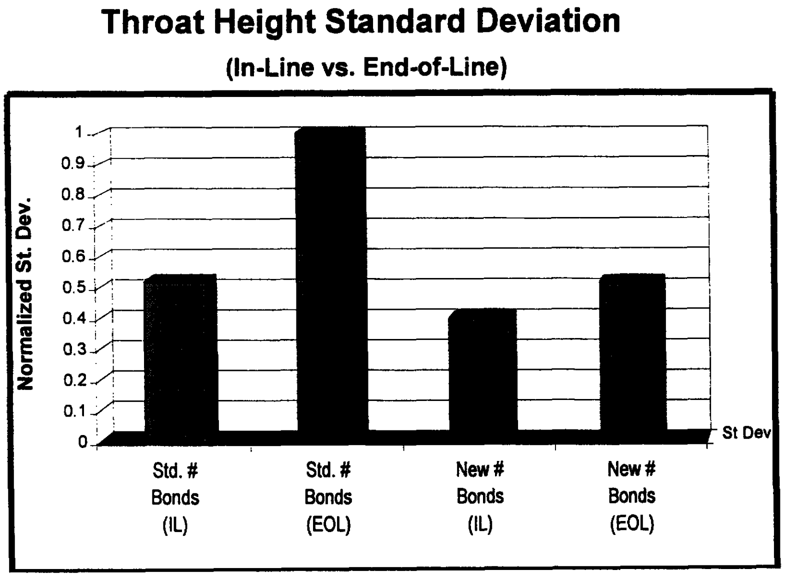


Figure 5-3. Electronic component height standard deviation vs. number of resistor bonds.

End-of-line variance on the NBP CLL material was 50% lower than on standard CLL material - this directly translates into significantly higher outgoing ceramic part quality. The lower variation also translates into higher product yield, especially for new product with much tighter outgoing ECH specifications.

Clearly the Cpk and variance of the end-of-line cross-section data is worse than the in-line electrical data. Since the NBP CLL data provides better end-of-line capability and variance results, the primary cause of the discrepancy appears to be interpolation/extrapolation errors due to sub-optimized input data point quantity.

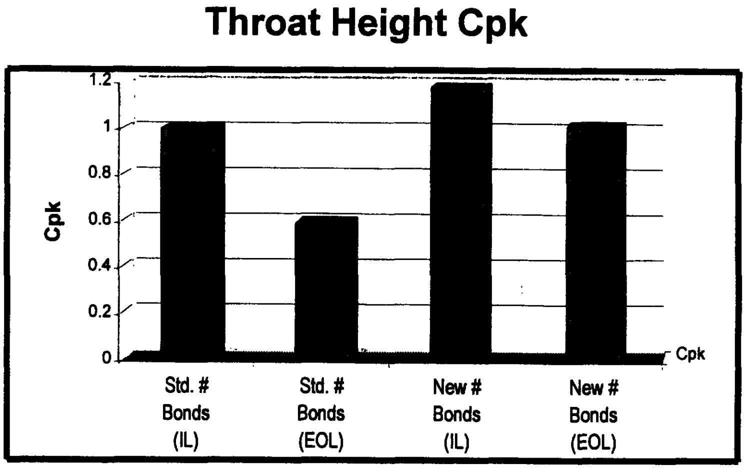


Figure 5-4. Electronic component height process capability vs. number of resistor bonds.

Impact of Number of Good Bonds

Electrical bond quality has been a problem since production turn-on. In order to show operators the importance of good electrical bonds the end-of-line data was broken out strictly by number of good bonds.

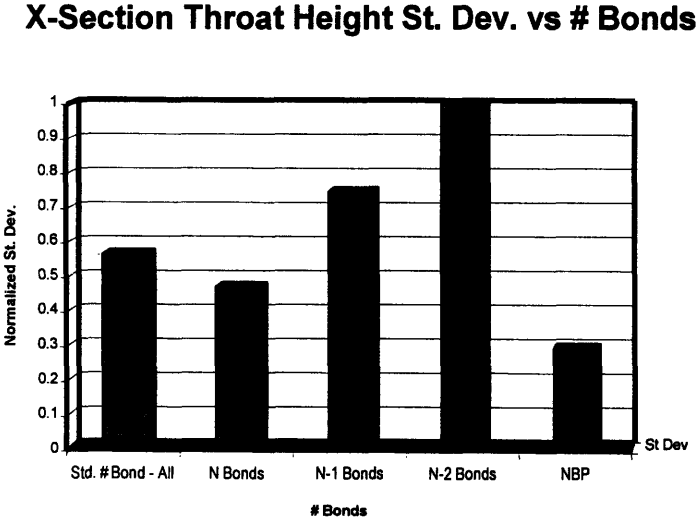
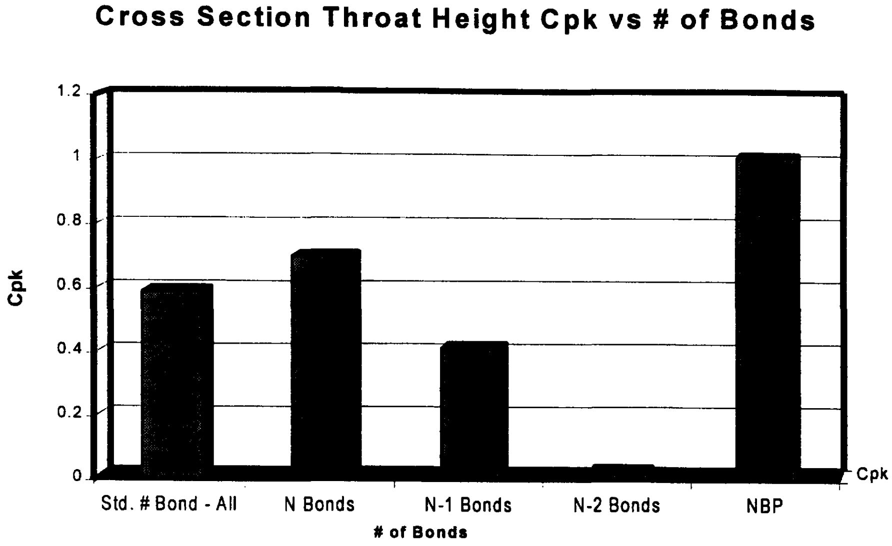


Figure 5-5. Throat height cross-section comparison vs. number of good resistor bonds

The cross section metrics of Standard Deviation and Cpk indicate a direct correlation between number of good bonds and end-of-line throat height process capability. The only process to provide a Cpk > 1 is the NBP CLL process.



Cpk is the best metric to quantify process robustness. Cpk is the minimum of Cpu and Cpl (the upper and lower spec capability metrics.) A robust process is defined as having a Cpk of at least 1.00, while 1.20 is desirable.

Figure 5-6. Process capability (Cpk) comparison of throat height cross-sections

A similar analysis was later performed during the engineering pilot line. End-of-line cross-section standard deviation was 33% higher than on the in-line measurement of the same material. The sample size was much larger with 73 cross-sections analyzed. Cpk was 1.25 for in-line and 0.96 for end-of-line throat height during the pilot line.

ECH Standard Deviation vs. Implementation Phase

CLL development consisted of three distinct phases: engineering development, engineering pilot line, and production line implementation. Each of these phases had unique issues and problems inherent with resourcing, training, data analysis and management support. Figure 5-7 displays the change in throat height standard deviation distribution over the course of the internship.

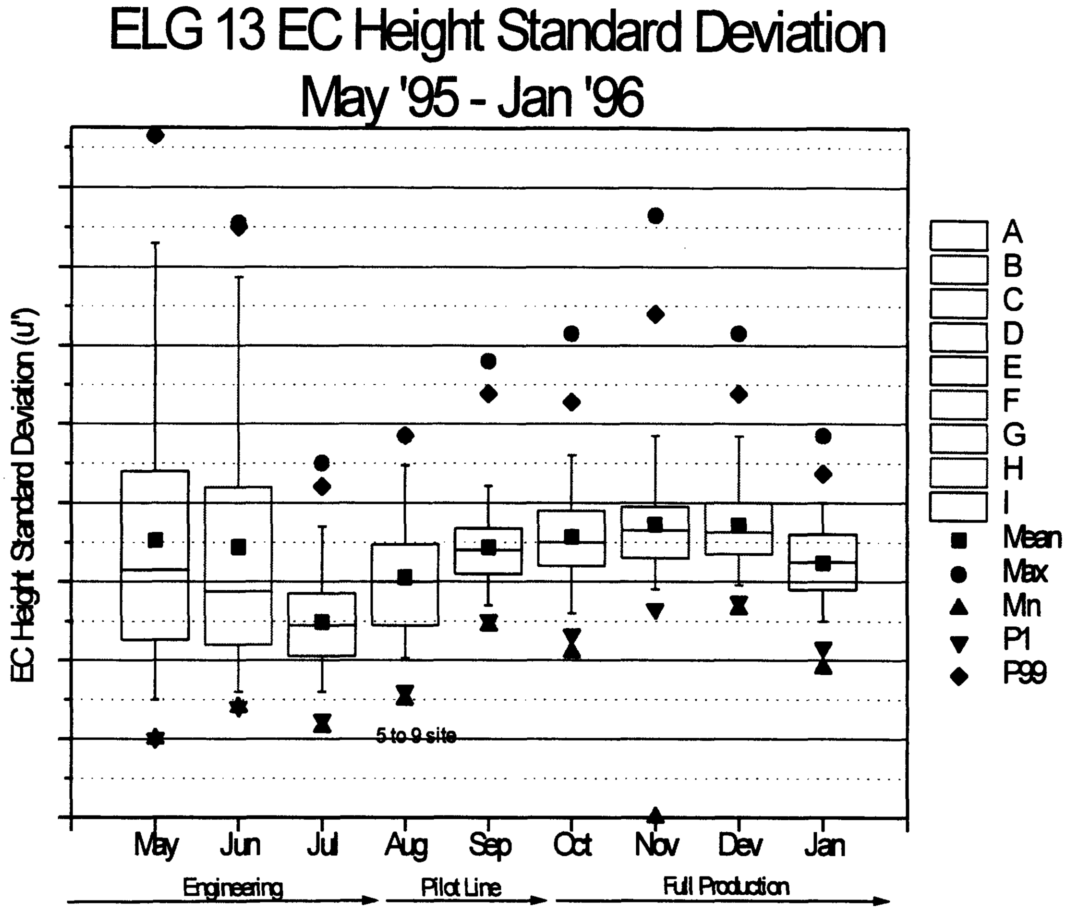


Figure 5-7. ELG 13 ECH standard deviation vs. CLL process date.

The engineering development phase reduced the range, average and median of the throat height standard deviation. Throat height standard deviation increased during the pilot line phase, in part due to the increase in lap sample size but also due to the learning curve associated with production operator training. Throat height standard deviation was slow to show improvement during the production phase - major improvement did not occur until late December and early January. In-line electrical throat height standard deviation trends for both the standard process and the CLL process are shown in Figure 5-8. The October increase of both processes was partly due to changes in product type. The learning curve of the standard process mirrored the CLL process during this time frame. The learning curve of the standard process prior to the internship was not quantified.

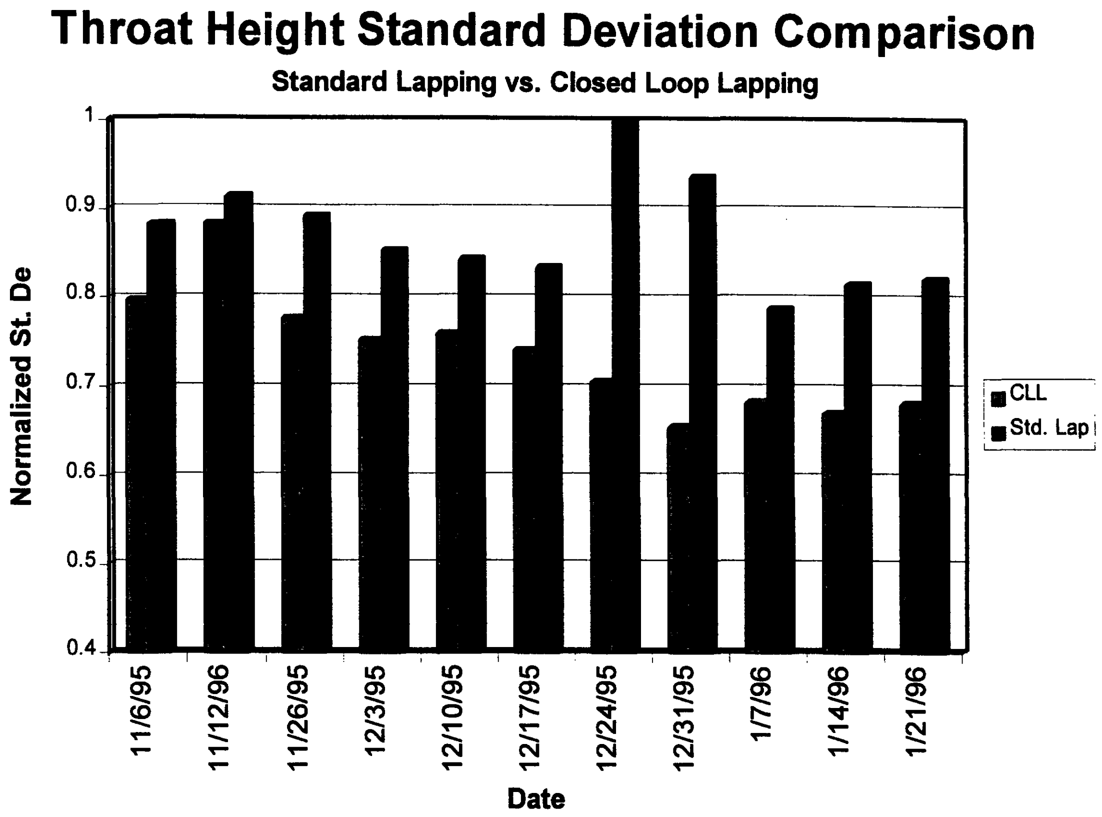


Figure 5-8. Standard Deviation Trend - Std. vs. CLL Lap Process.

End-of-line throat height cross-section analysis was completed on production material processed on both the standard and CLL process. Cross-section analysis [Figure 5-9] indicates that the CLL process in volume production has a 18.15% lower variance than the standard process and a mean value less than 1% off the standard process mean.

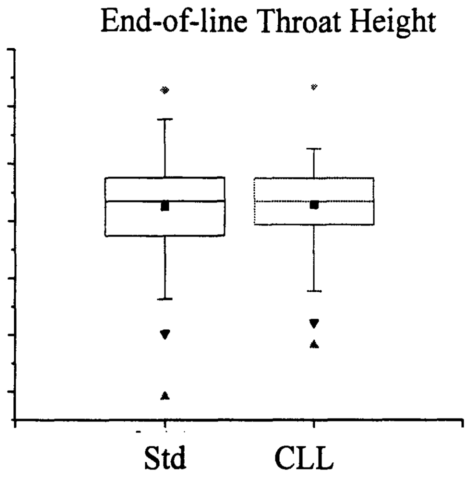


Figure 5-9. Throat height end-of-line cross-section comparison of CLL vs. standard process..

CLL throat height standard deviation is expected to improve further over standard production as operators progress on their CLL process learning curve. The volume production process is still not operating at the levels found during the engineering phase.

Cross-section data indicates that CLL has a tighter end-of-line ECH distribution than the standard process [Figures 5-10, 5-11] but it still has significant tail distributions as shown in the non-linear CLL probability plot. A primary cause of end-of-line variance is poor resistor bond quantity as discussed previously.

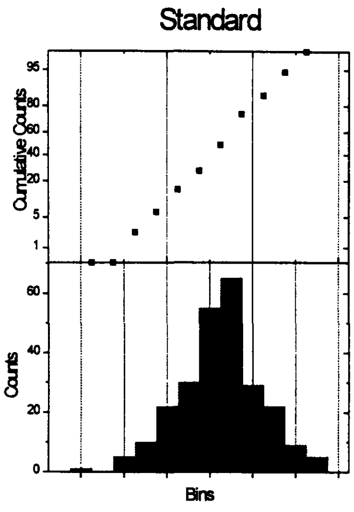


Figure 5-10. Throat height cross-section distribution analysis of standard lap process.

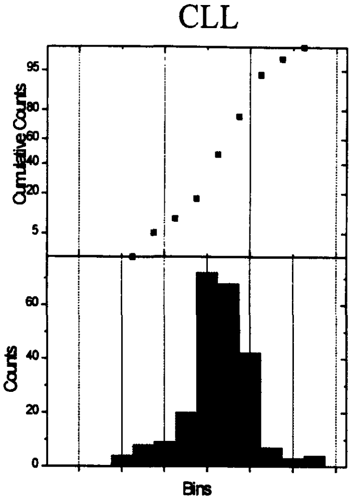


Figure 5-11. Throat height cross-section distribution analysis of CLL lap process.

Analysis of Actuator Final DDT Values

A useful metric for CLL process capability analysis is the *final DDT position.* This value is recorded in a database for every ceramic row processed on the CLL process. The final DDT position should be 400 u" if the process was centered with regard to actuator extension capability. The final DDT value is not a true reading of actuator extension. It is a translation of the voltage applied to the actuator and is based on a 4 step voltage to extension correlation table.

Changing the process flow from a 150 volt pre-charge/400 u" Row Bow to a 60 volt pre-charge/0 u" Row Bow decreased a left/right DDT disparity. The exact cause/effect of the decrease is not understood and the process flow change is compounded with changes in pin style and transfer tool pre-bow. The procedural order of Row Bow is also felt to impact the offset. Most operators initially adjust the left actuator, and this adjustment does impact the right actuator value. A trial procedure was established for a week where Row Bow flow was changed to the adjustment of the right actuator first and minimal offset enhancement resulted.

Final DDT vs. Implementation Phase

Similar to ECH variance changing with CLL development, the actuator DDT distribution changed with implementation phase. The early production phase had worse DDT variance than the pilot line phase as operators were low on the new Rob Bow and CLL learning curve.

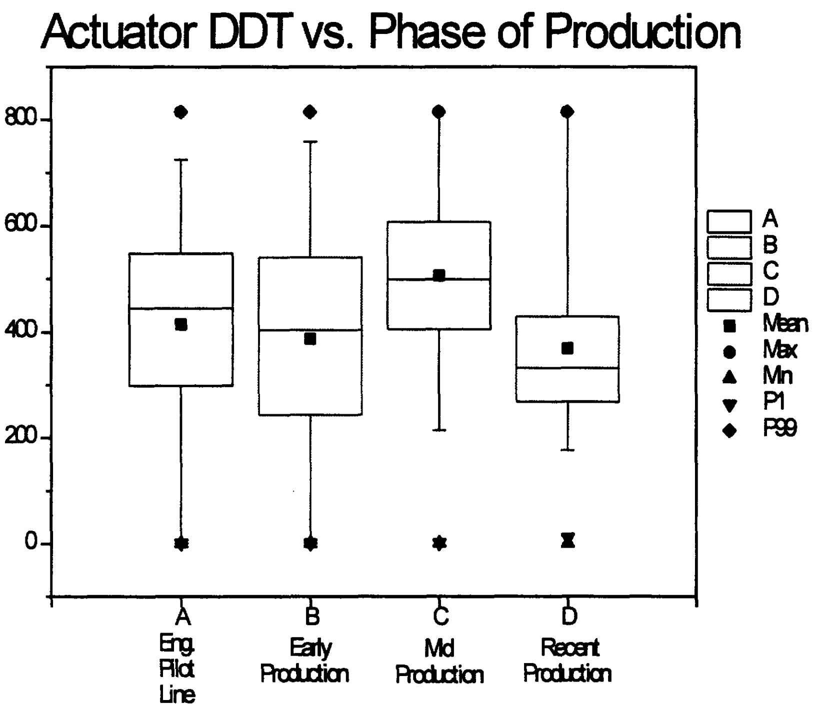


Figure 5-12. Final DDT value vs. CLL implementation phase.

Significant physical abuse of the module block components on unsupervised weekend shifts caused many "max out" scenarios. Linkage loss and poor tool pre-flatness caused high "min out" levels during the pilot line and early production phases.

Changing the pre-charge voltage from 150 to 60 volts and lowering the Row Bow target from +400 u" to 0 u" caused a significant decrease in "min outs" in the mid-production phase of December. Further "max out" decreases were achieved in January with pre-charge voltage being lowered even lower to shift the DDT distribution lower. The DDT distribution was tightened with the implementation of thick head transfer pins, -1000 u" pre-flatness tool bars, and better preventative maintenance procedures on module blocks. The timeline of change in Final DDT distribution is further broken down in Figure 5-13 with all production DDT values from one CLL lapper plotted vs. processing date.

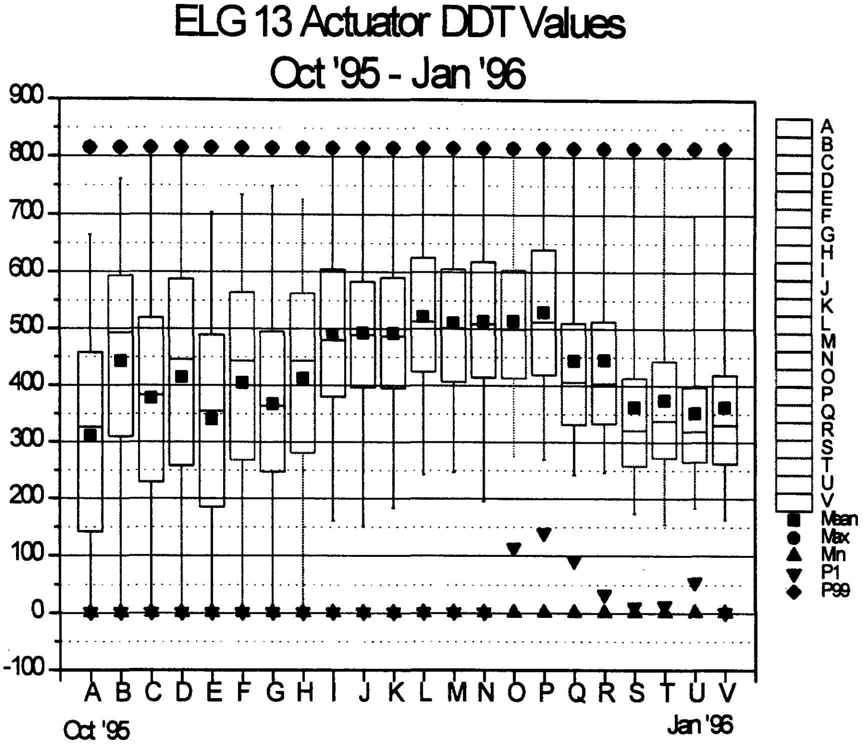
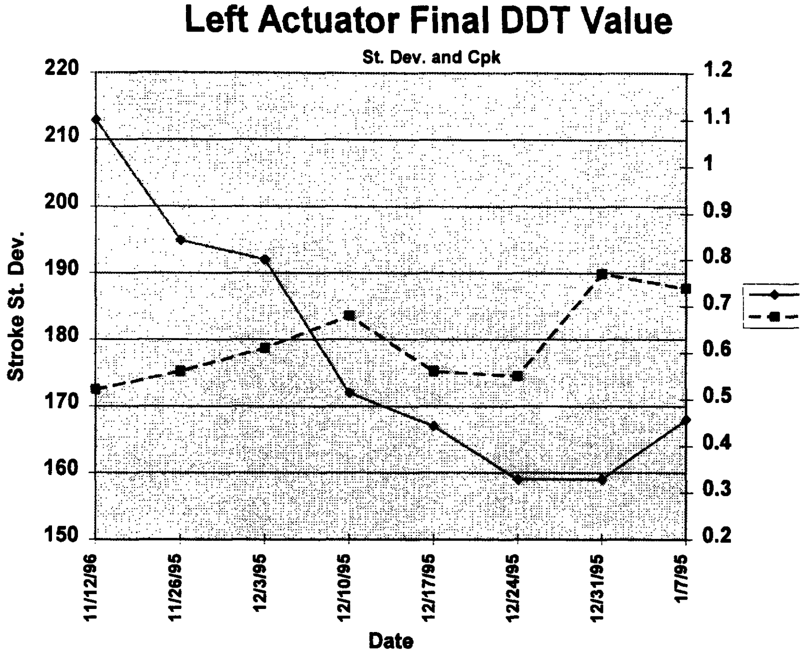


Figure 5-13. ELG 13 Final DDT value vs. CLL process date.

Another way to quantify DDT distribution is through average standard deviation analysis vs. CLL process date [Figure 5-14]. One sigma values of 213 u" were tightened to <170 u" with the previous stated process changes.



As expected, Cpk improves with a decrease in standard deviation. Cpk or process capability was defined for this process with an upper specification equal to a "max out" scenario and a lower specification equal to a "min out" scenario.

Figure 5-14. Final DDT standard deviation and process capability vs. production date.

Production Process Yield

Unlike the engineering phase, the CLL process yielded lower than the standard process during the full production phase. Figure 5-16 shows that the yield gap between the new and old process is closing, and it appears that the CLL process will obtain better yield than the standard process in the near future. The yield increase is directly dependent upon throat height variance decreases, as a ceramic slider is assigned a loss code if its throat height variance is out of specification limits.

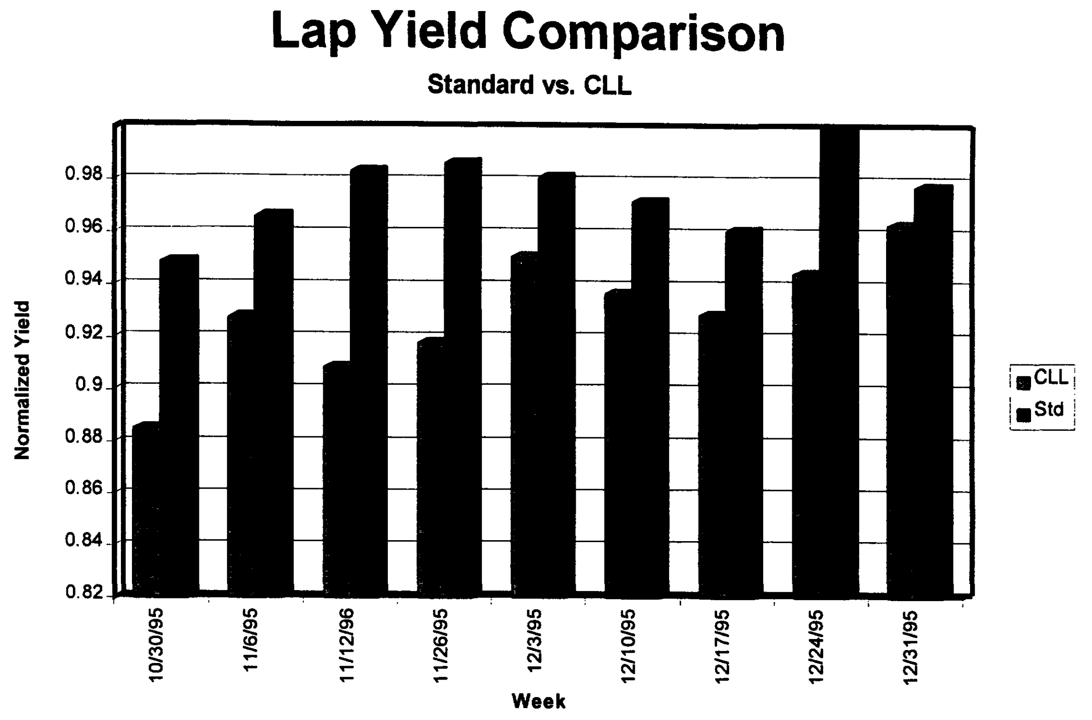


Figure 5-15 Lap Yield - Standard vs. CLL Process

Deficient ceramic sliders are assigned loss codes at lap. Loss code quantity is uploaded to the mainframes with lot and equipment association. Figure 5-16 quantifies each of these loss codes on a weekly basis for 4 months of production.

- LIMIT - Actuator limit reached - "min out" or "max out" scenario
- NoBond - Resistor bond failure
- Operup - the operator stops processing on the row for various reasons
- Barmin - minimum number of good bonds was reached
- Badres - electronic lapping guide resistor is bad
- Underlap - the slider ECH is too high - over upper spec limit
- Overlap - the slider has been over lapped - ECH is too low

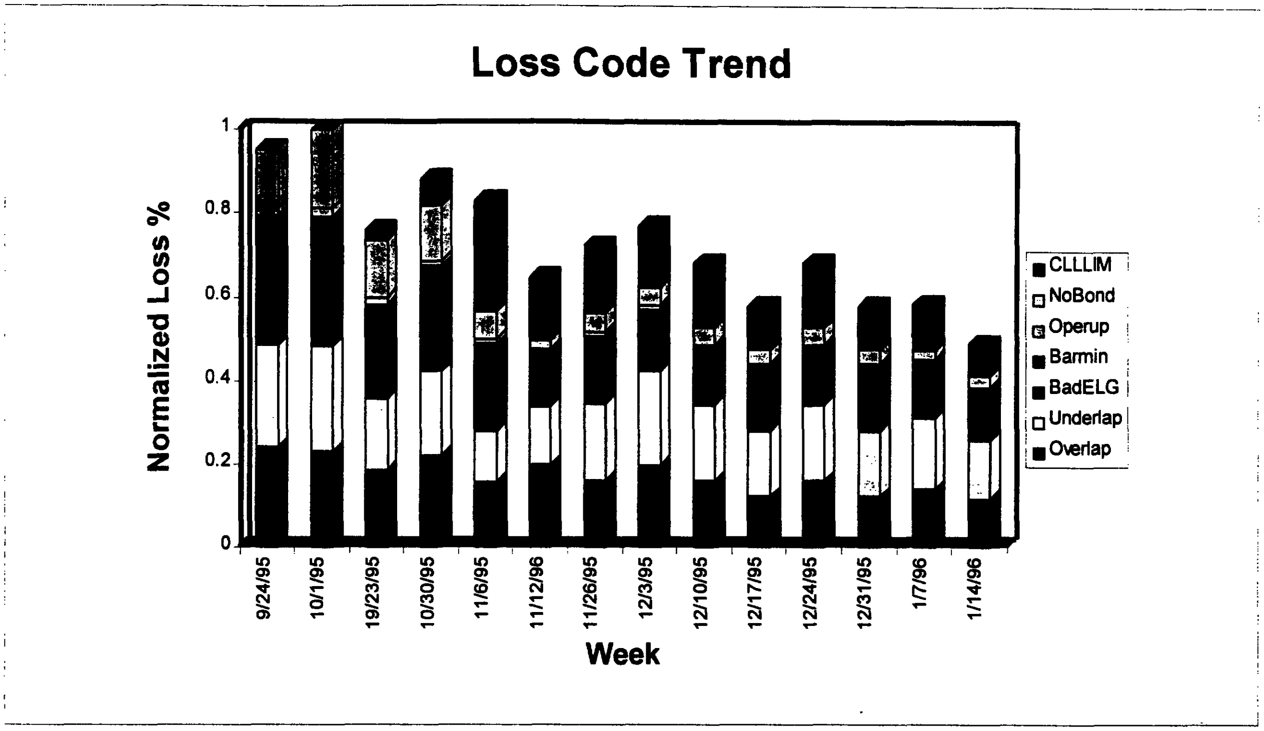


Figure 5-16. CLL Losses by Loss Code and Date.

Note that loss code CLLLIM did not start until mid November. This loss code was created from portions of the other loss codes such that CLL induced losses could be directly tracked. Without CLLLIM the engineering staff did not have a metric for showing improvement vs. hardware or software change. From October 1995 to January 1996 the CLLLIM losses were decreased by ~70%.

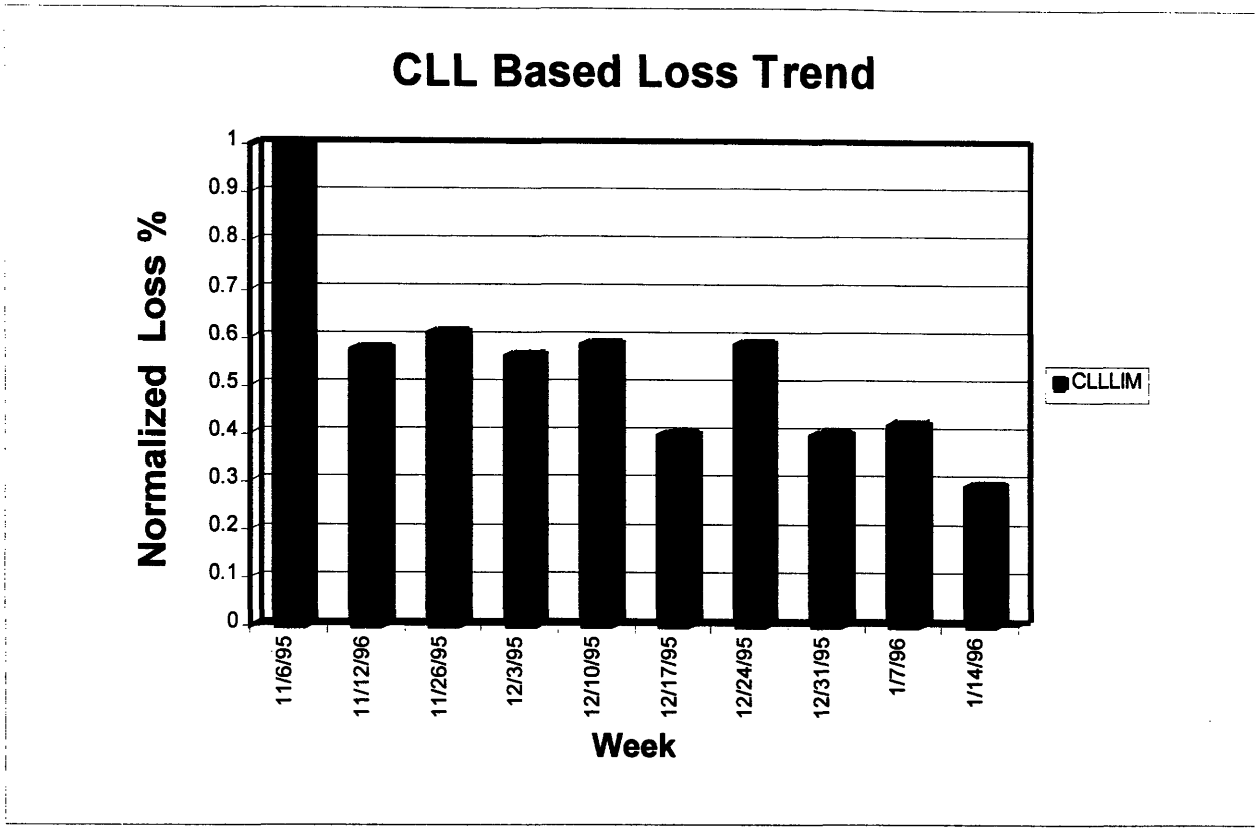


Figure 5-17 Lap Loss Code CLL_Lim improving over time.

Ramp losses are inherently higher on the CLL process because the transfer tool is more flexible and the module block has much higher potential for changing slider position than with the standard process. One of the main concerns discussed in chapter 3 is the discharging of the actuator. Any voltage loss directly translates into a decrease in the bow of the ceramic row. If the bow decreases between CLL lap and ramp lap a yield loss will occur, as ramp lap can not correctly process a non-linear row.

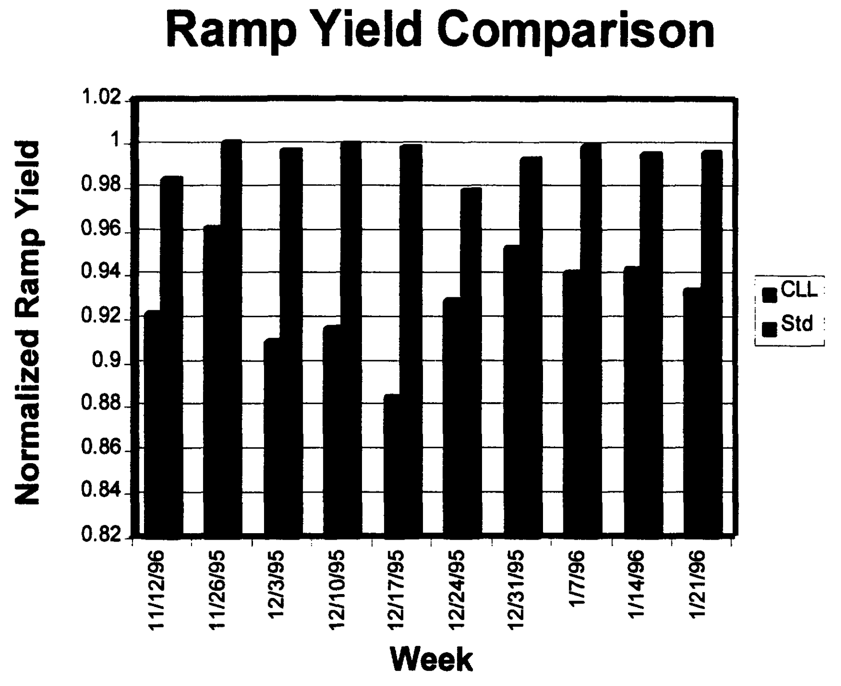


Figure 5-18 Ramp Yield - Standard vs. CLL Process

Several "fixes" have been implemented by the engineering team to decrease the susceptibility to discharge - these include actuator potting, cable connector isolation, change of tool clean procedures, and training of the operator. Actuator discharge will be a concern until either ramp processing is done on the CLL or ramp is completed without a lap operation.

The first step towards knowledge is to know that we are ignorant.
Richard Cecil

Real knowledge is to know the extent of ones ignorance.
Confucius

It takes a long time to understand nothing.
Edward Dahlberg

The intellignet man is one who has sucessfully fulfilled many accomplishments, and is yet willing to learn more.

Ed Parker

Chapter 6: External Focus and Analysis

This chapter is quite different from the previous chapters, because its primary emphasis is the use of external focus to improve manufacturing policies and procedures. By looking beyond its own boundaries of brick and mortar, an organization can continuously improve its people, procedures, equipment and facilities. An LFM internship is part of this external focus, as the lens that the LFM student looks through can be very different than the lens of the company. By seeing things in a dissimilar or unique manner the intern may be able to help individuals in the company see things that went unnoticed with the old lens. This isn't to say that the current company lens is bad; a diversified viewpoint can lead to heightened awareness.

Individuals and companies have blind spots in their strategic vision. We are all curious about the "blind" quadrant of the Johari window shown below, as only others can help us see subconscious actions that may either be a detriment or are simply not exploiting a given strength.

	Known to Self	**Not Known to Self**
Known to Others	*Open*	*Blind*
Not Known to Others	*Hidden*	*Unknown*

The content expert role that an intern may play in a given organization can be very important for the short term, but a foundation must be laid for the long-term success of the manufacturing environment. By being exposed to an external environment, the manufacturing firm is more apt to practice a Best Known Method (BKM). Benchmark activity, vendor analysis and external/internal consultation all play an important role in the externally focused improvement methodology, and are discussed in detail.

> *It is not always by plugging away at a difficulty and sticking at it that one overcomes it; but, rather, often by working on the one next to it. Certain people and certain things require to be approached at an angle.*
>
> André Gide, 1924

Competitive Benchmark

McNair and Leibfried [39] define benchmarking as '*an external focus on internal activities, functions or operations in order to achieve continuous improvement.*' Benchmarking can allow a company to either gain a competitive edge or to simply catch up. Xerox was the first major U.S. corporation to practice benchmark activities in an attempt to meet Japanese challenges. Many large U.S. and Japanese firms now conduct both internal and external benchmark activities. The primary aspects of benchmarking are:

1) Identify the activity, function or operation that requires improvement.
2) Identify the best known method or practice.
3) Analyze the BKM.
4) Identify the components of the BKM that are applicable.
5) Implement components.

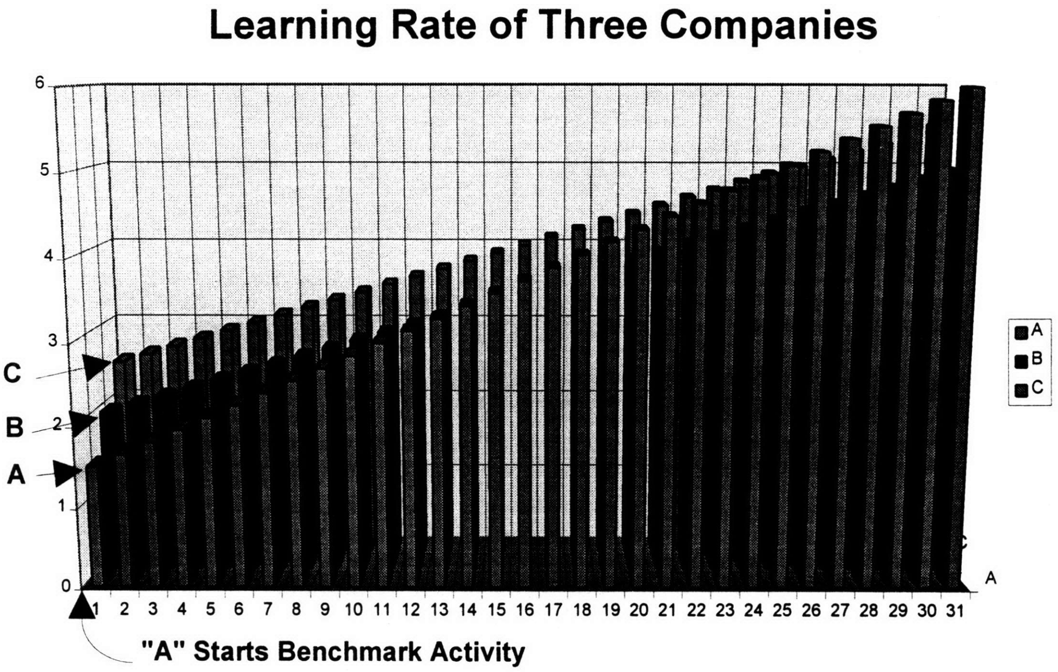


Figure 6-1. Learning rate of company A is higher due to benchmarking activity.

Benchmarking increases the competitive nature of a company because its learning rate is higher than industry rivals. The learning curve for a fictitious metric is shown in Figure 6-1 for 3 companies. If company A starts benchmarking at time zero it will eventually pass companies B and C.

Four distinct areas were benchmarked during the internship and are described in detail either below or in other chapters. The benchmarks characterized an external mechanical positioner, external equipment manufacturers, vendor actuator characterization techniques, and various types of actuators. The company was very open to any external focus activity and readily provided funding.

Mechanical Positioner

A high-end (expensive) electrostrictive mechanical positioner was purchased and reverse engineered. The learning's from the benchmark were incorporated into the next two internal designs. The key design features of the positioner were significant improvements over the current internal technology, including:

- Mechanical interface contact design using a ball bearing and an optical flat
- Wire wrap style and restraint technique
- Course adjustment mechanism
- Hermetic seal using Teflon tape on treaded cap
- Electrical connector quality
- Electrical insulation technique

External Lapper

Two lap equipment vendors were benchmarked by the internal engineering team. The chapter 7 economic study compares and contrasts several significant advantages and disadvantages of the external machines with regard to the internal equipment development strategy.

Electrical Characterization Techniques

The actuator characterization techniques [43] discussed in chapter 5 are the result of a benchmark activity with both the actuator vendor and knowledgeable internal engineers. Two types of electrical tests involved a $30,000 electrical characterization station and a highly trained technician. The best known method turned out to be the simplest: using a $400 high resistance ohmmeter an operator bins out actuators to various loss codes with each loss code representing a specific failure mechanism. Engineering is expected to respond and correct significant failure modes in a *plan-do-check-act* cycle.

Enhanced communication is an additional advantage of using the vendor's electrical characterization procedures. When actuators failed the electrical test due to short term leakage, vendor discussions resulted in experimental designs for fault isolation.

External Ceramic Actuator Manufacturers

Electrostrictive actuators have high unit costs due to limited use in other applications. Other types of actuators, such as piezoelectric, were analyzed with technical literature and vendor contact, but none could match the electrostrictive properties of charge hold, high strain, minimal size, and low voltage.

Actuator Vendor Audit

An audit of the actuator vendor's manufacturing facility provided a key external focus for both the vendor and the auditor. Establishment of a good working relationship enhanced future technical problem communication and also allowed product road-map discussions.

The vendor's production line for the electrostrictive actuator is not cost effective, as it is essentially an experimental pilot line. The vendor's long-term goal is to use a high volume/low cost capacitor manufacturing process to make electrostrictive actuators. This would result in a 95% unit cost reduction, but the unit volume increase would need to be significant and the performance of the new style actuators is greatly reduced.

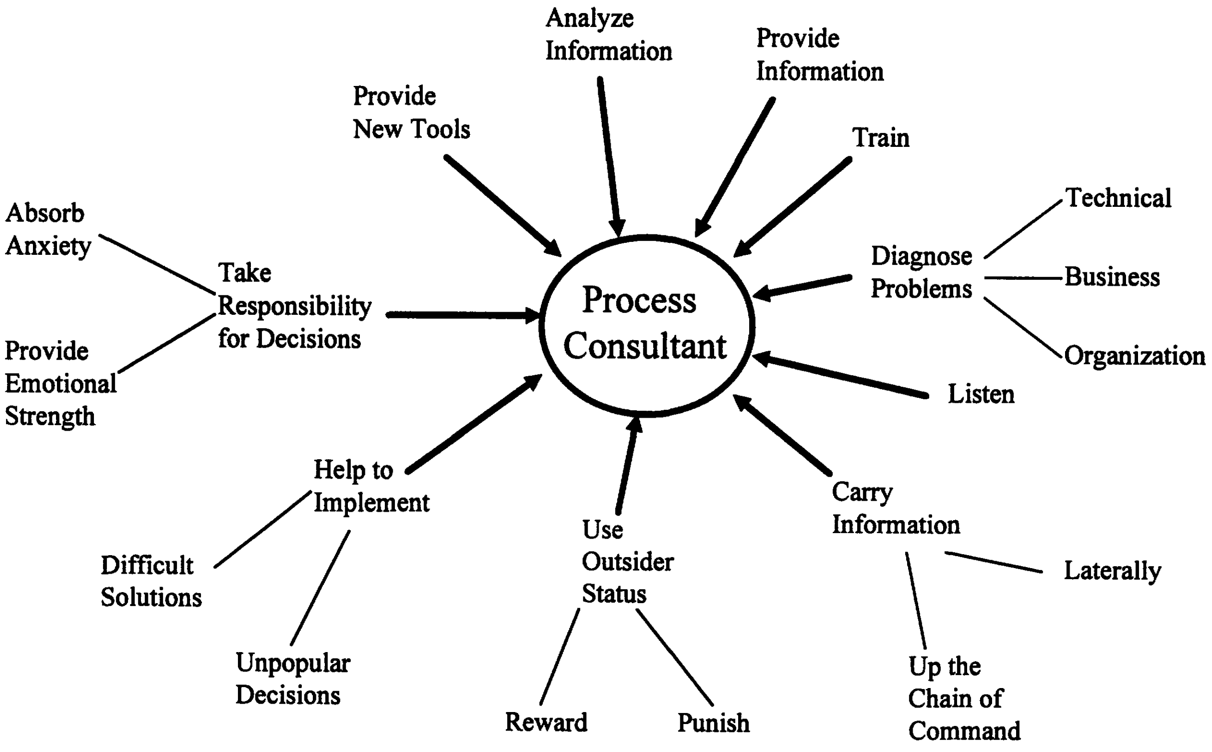
Various "moonie" mechanical amplification designs [49] were discussed with the vendor. These devices provide increased stroke but reduce the applied force. Several designs were submitted for internal build, but were not finished during the internship time-frame.

> *Process consultation is a set of activities on the part of the consultant that help the client to perceive, understand, and act upon the process events that occur in the clients environment.*
>
> Edgar H. Schein 1987

Determining the Role and Benefits of an Internal Consultant

Internship Consulting Roles & Responsibility

Schein [58] differentiates between three different models of consultation: the purchase of information or expertise model, the doctor-patient model, and process consultation. The expertise model is appropriate when clients have diagnosed their own needs, have identified consultant capabilities, and can communicate well. The doctor-patient model is appropriate when the client is experiencing clear symptoms, knows where the sick area is, and is willing to become dependent on the consultant for both diagnosis and implementation. Schein describes the process consultation model premise as the client owns the problem and continues to own it throughout the consultation process. The model is appropriate for a learning organization [60]. The client not only needs help in resolving the problem but would benefit from participation in the problem diagnosis procedure. Schein suggests that a consultant fills the following roles:



During the internship each of the three consultation models were used at various points, but the emphasis was on the process consultant style model. I was not an expert in any one of the key technical areas (mechanical design, equipment building, ceramic lapping) but I was a content expert in problem analysis and resolution. There were several internal content experts for each of the technical areas. The relatively short time-frame of the internship (6.5 months) dictated the Process Consultant style to be the most beneficial to the sponsoring firm. If I could provide some additional problem solving skills or tools to the clients, the value of the internship would be much greater than just the time that I spent with them on the manufacturing floor.

Lewicki et al[i] describe several key attributes of a process consultant: they should be perceived as an expert in the technique, knowledgeable about conflict and its dynamics, be perceived as neutral if there is an internal conflict, and should be able to establish power over the process of the item that they are consulting on. The last point is fairly important for an LFM intern; if the intern has no source of power he will not accomplish the desired task. The source of power doesn't have to be legitimate authority, but can be expert, resource, reward, coercive, or referent power. Expert power is strong initially in the internship, but will be tested continually. Resource power may be weak initially but will grow as the intern accomplishes tasks or the problem resolution becomes more desirable. Legitimate power grows as the intern establishes himself, and may be high at the start if the intern has a strong sponsor, which I was fortunate enough to have. Various personal sources of power that will help the task proceed are persuasion, friendliness, praise, assertiveness, relationship and situational emotionalism.

Problem Analysis

Previous work experience in technical volume manufacturing and MIT course work, specifically the TQM [61] and System Dynamics [100,101,60,21] courses, allowed several problems to be traced to root causes in a systematic fashion. The problems were attacked in a PDCA cycle similar to the Shiba TQM 7 Step Improvement Process shown in table 6-1.

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[i] Lewicki, Roy J., et al, Negotiation, Irwin, Burr Ridge, Illinois, 1994.

Table 6-1 TQM 7 Step Improvement Process and Quality Tools

7 Step Improvement Process	7 Quality Control Tools
1. Select Theme	***1. Check Sheet***
2. Collect and Analyze Data	***2. Pareto Diagram***
3. Analyze Causes	***3. Cause and Effect Diagram***
4. Plan and Implement Solution	***4. Graphs/Stratification***
5. Evaluate Effects	***5. Control Charts***
6. Standardize Solution	***6. Histogram***
7. Reflect on Process and Next Problem	***7. Scatter Diagram***

The problem solving methodology used during the internship was not identical to the 7 Step Method. The method used was geared towards the specific needs and resources available at the company, and it was influenced by my prior experience in a similar manufacturing environment. The iterative nature of a PDCA or 7 Step problem solving method lends itself well to a variation reduction scenario. Variation reduction is analogous to the peeling of an onion; the outer layers must be attacked and removed before the inner layers are shown. When all elements of variation of a system are viewed together, no apparent complete solution can be found; variable interaction clouds the analysis. The individual variation sources must be separated and reduced in a systematic fashion, with the highest pareto items attacked first. Some elements are impacted by production or engineering tools, policies and procedures and thus are more long-term in nature. Strategic (long-term) and immediate (short-term) problem solving methods needed to be done in parallel due to the short (6.5 month) nature of the internship.

Short-term Problem Solving Example

An example of a short-term problem solving method used during the internship was the "815 max out" problem, discussed below. Portions of the 7 step method will be used to illustrate the problem analysis procedure.

Select Theme

Discussion with key content experts highlighted an initial theme:

During the engineering evaluation period of the CLL process an intermittent problem has caused high variability and has limited further process characterization and implementation. During the lap process the actuator would "max out" at 815 micro inches (u") with apparently an inadequate force being applied to the tool position. This results in a diminished polish rate for that lap position and a yield loss of the ceramic row (or portions of the row). The problem is intermittent in nature, and is a roadblock to the transfer of the closed loop technology to other sites.

This theme was indeed a business priority, as it was severely impacting the manufacturing implementation and characterization of the new closed loop lap process. The transition to smaller throat geometry requires improvement in the process variance, as the throat height variance correlated directly to manufacturing yield. The yield of new products with minimal throat height is vital to this companies continued technology leadership position. Resources were easily obtained for the project due to it negative impact. Team members area of responsibility included content expert from equipment design, lap process, equipment software, database software, machining, and the analytical lab.

Improvement goals were established and communicated to the group, along with the business priority and the projected impact of the project. Initially the project scope was inclusive of all aspects impacting the variance of the electrical throat height, but it was later pruned to the primary mode of "815 max out" failure. Project stakeholders included the equipment development group, manufacturing engineering, production, the actuator vendor, 3 other manufacturing sites, myself, my advisors, and MIT.

Collect and Analyze Data

The problem metric was defined as the frequency of occurrence of the "max out" event and the overall lap electrical throat height standard deviation. It was vital to establish key metrics early in consultation process, as both long-term and short-term database improvements geared towards variation reduction could be started. Data was collected for the key metrics for both the standard and the closed loop process.

Analyze Causes

Fishbone diagrams were made of possible problem modulators including equipment, process, procedure, materials, and people. Several areas were analyzed but the key areas appeared to be 'slippage' in the actuator linkage to the tool bar interface, and a procedural/materials error in the discharge of actuators to a baseline condition.

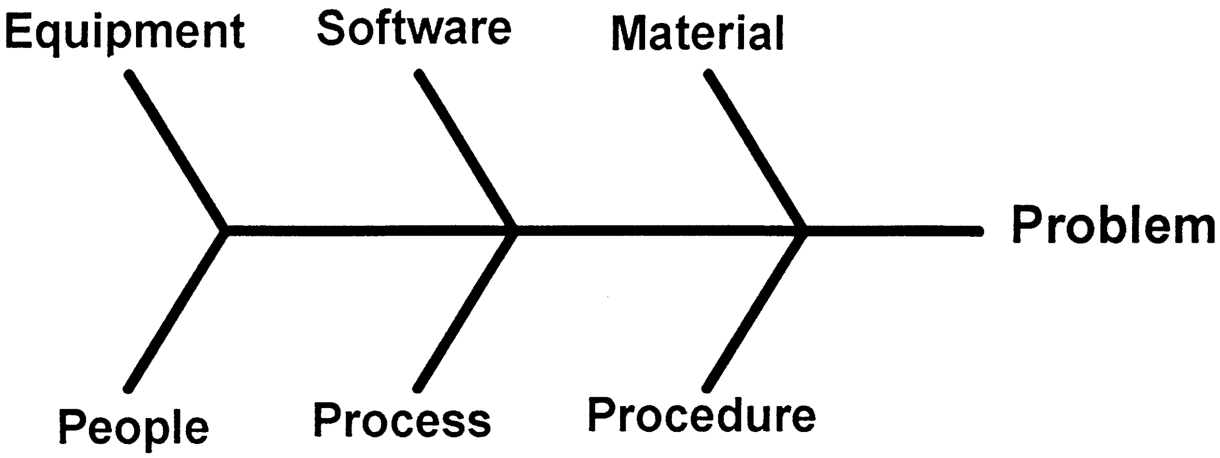


Figure 6-2 Standard Fishbone Structure used Throughout Internship.

Plan and Implement Solutions

The two paragraphs below describe the "solution" as noted at the time:

> The slippage was resolved with a new pre-lap process procedure that forced the actuator to tool linkage to be 'tight'. The previous process included an actuator 10 kohm discharge and hence a zero actuator extension condition. This was followed by a set screw tightening until tool displacement occurred. Theoretically this was the best possible condition, as the ELG software was programmed for an initial 400 micro inch (68 volt) extension, and the incoming bars should have a negative 400 microinch bow, thus resulting in a flat surface. The CCL process would then use feedback from resistors on the head and an adjustment algorithm to polish the head to a specified throat height. Unfortunately two different types of 10 kohm resistors were in use for discharge and one type only partially discharged the actuators, thus leaving a random occurrence of actuator initial conditions that varied from 0 to 70 volts. Also, several actuators were found to have rapid charge decay - these were replaced and new tested block sets were created.
>
> The new procedure includes backing out the actuator, full discharge, charging to full extension (150 volts), and row bow to a +400 (positive bow) state before ELG. The initial ELG condition (68 volts from 150 volt incoming) would allow a back off from the +400 u" condition to a flat bar condition, and minimizes linkage slippage. Slippage is minimized due to a high force being applied to the linkage before the back-off. It is thought that the two ball/cup interfaces cause >400u" of slippage or lost extension when everything in the linkage is not perfectly aligned. The new procedure minimizes this problem, but a new design is required to eliminate this variation modulator.

Reflect on Process and Next Solution

Other modulators are currently being studied, but first a valid data base and operator training must occur. Properly trained operators are able to achieve a variance of less than 5 u" with the new process. Near term improvements include optimized module block Row Bow, 9 point flex cable, and improved ceramic tip surfaces, and establishment of data base and process analysis tool set (pareto, capability, trend, entity and block comparison routines). Longer term improvements include block redesign, actuator redesign, and ramp process.

Long-term Problem Solving Example

Continuous Improvement and Innovation

Complacency is the archenemy of continuous improvement - doing one root cause analysis is not enough. Improvement must be standardized and built into a process. Imai [] asserts that Japanese are process oriented while the US is a results oriented society. If the reward or incentive systems are tied into continuous improvement processes, then the person or group will continuously grow. Imai translates the Japanese phrase "kaizen" as a process-oriented way of thinking and developing continuous improvement processes at all levels in an organization.

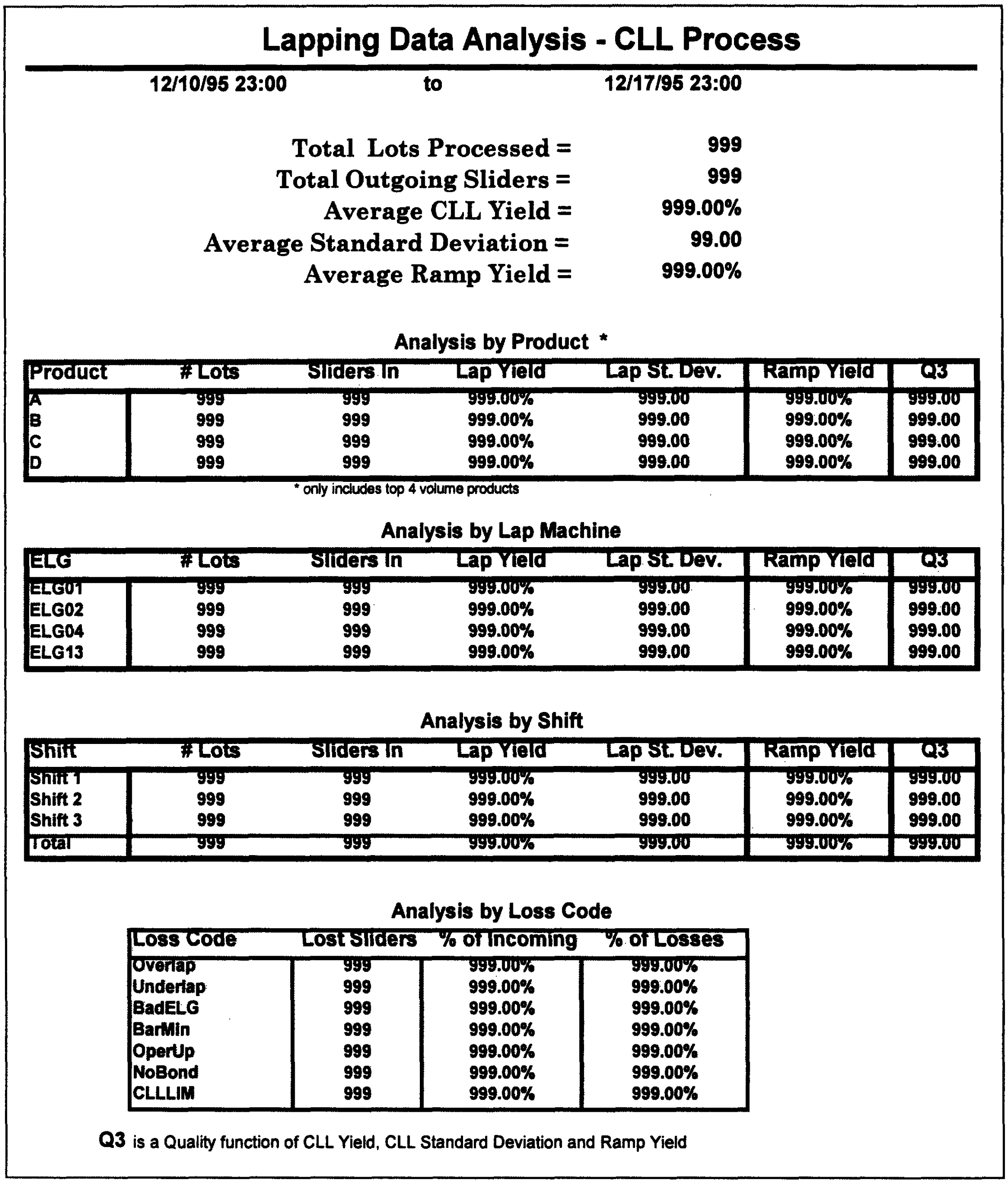
Kaizen is a customer driven strategy for improvement. The voice of the customer must be heard and understood for the product to do well. This has been a powerful concept in most of my MIT classes including TQM, product design, strategy and marketing. One concept that Imai doesn't touch upon was the main point that I gained from Shiba's class: "swim with the fish". When you are trying to understand a customer's problem, do not just ask them about it or try to come up with theory, but go into that environment and completely understand the issue. When I swam with the fish I did not see many variance reduction decision that were data driven. If more data driven decisions were to be made the information technology systems had to be modified; this is discusses in the next example.

Data Analysis Software Programming

A systematic data driven problem solving approach was integrated into the slider engineering and production environment through the use of information technology. Figure 6-5 is an example of the automated weekly report's cover sheet. This report has been in use for over 4 months and is used by both engineering and production for process analysis and improvement. The following are the significant aspects of the report:

- ***CLL vs. Standard Process Comparison***
- ***Equipment Comparison***
- ***Module Block Set Analysis***
- ***Shift to Shift Analysis***
- ***Product to Product Analysis***
- ***DDT Process Capability***
- ***Quality Factor Analysis***

By comparing and contrasting the key metrics of the standard and CLL process the report places emphasis on gap analysis. When a key metric is significantly different on the new process both engineering and production personnel should be able to start a new plan-do-check-act (PDCA) cycle and systematically eliminate the problem.



Lapping Data Analysis - CLL Process

12/10/95 23:00 to 12/17/95 23:00

Total Lots Processed = 999
Total Outgoing Sliders = 999
Average CLL Yield = 999.00%
Average Standard Deviation = 99.00
Average Ramp Yield = 999.00%

Analysis by Product *

Product	# Lots	Sliders In	Lap Yield	Lap St. Dev.	Ramp Yield	Q3
A	999	999	999.00%	999.00	999.00%	999.00
B	999	999	999.00%	999.00	999.00%	999.00
C	999	999	999.00%	999.00	999.00%	999.00
D	999	999	999.00%	999.00	999.00%	999.00

* only includes top 4 volume products

Analysis by Lap Machine

ELG	# Lots	Sliders In	Lap Yield	Lap St. Dev.	Ramp Yield	Q3
ELG01	999	999	999.00%	999.00	999.00%	999.00
ELG02	999	999	999.00%	999.00	999.00%	999.00
ELG04	999	999	999.00%	999.00	999.00%	999.00
ELG13	999	999	999.00%	999.00	999.00%	999.00

Analysis by Shift

Shift	# Lots	Sliders In	Lap Yield	Lap St. Dev.	Ramp Yield	Q3
Shift 1	999	999	999.00%	999.00	999.00%	999.00
Shift 2	999	999	999.00%	999.00	999.00%	999.00
Shift 3	999	999	999.00%	999.00	999.00%	999.00
Total	999	999	999.00%	999.00	999.00%	999.00

Analysis by Loss Code

Loss Code	Lost Sliders	% of Incoming	% of Losses
Overlap	999	999.00%	999.00%
Underlap	999	999.00%	999.00%
BadELG	999	999.00%	999.00%
BarMin	999	999.00%	999.00%
OperUp	999	999.00%	999.00%
NoBond	999	999.00%	999.00%
CLLLIM	999	999.00%	999.00%

Q3 is a Quality function of CLL Yield, CLL Standard Deviation and Ramp Yield

Figure 6-3 - Example of Weekly Data Summary

Many key information technology and logistical issues had to be resolved before a technician could easily produce the previous report. Automated data collection procedures had to be rewritten by software engineers. To obtain the required future disk space and proper software modifications the database engineers had to be convinced on the validity of the project. Several weeks of data had to be generated before production and sustaining engineering agreed to the training of a technician on program generation. Once the program was generated several people were trained on reading and understanding the capability, trend and probability plots.

Hopefully the program will continue to be used in the future. Problems should be resolved quicker and new process problems should be highlighted sooner.

Ask five economists and you'll get five different answers (six if one went to Harvard).

Edgar R. Fiedler

Chapter 7: Internal/External Lapper Economic Analysis

The selection of next generation processing equipment hinges on managerial decision-making, which is based upon the current best-known information. This decision goes beyond simplistic cost-based accounting [36,40] and must take into account the following 5 factors:

Customer Satisfaction

Customers must be satisfied in order for the company to maintain a strong customer relations. Customers for the process/equipment development group include manufacturing, various internal and external final assembly houses, OEM vendors, and the end user of the product.

Key Success Criteria

It is vital that each of the following criterion be analyzed independently for each lap equipment option:

Cost:	Analysis of capital costs, wages, expense items, throughput, floor space requirements, machine uptime and utilization, etc.
Quality:	Mean inductive throat height, mean MR stripe height, mean ramp length, variance of throat/stripe height.
Time to Market:	The time it takes to successfully bring a new lapper or lap process on-line, characterize it, implement it into production, and transfer it to other sites. May also refer to problem resolution time.
Innovation:	A continuous flow of innovations is required if world class status is to be achieved. Equipment innovation is dependent on ease of change implementation and departmental core competency.

Value Chain Analysis

Horngren [36] believes that there are two main aspects of a typical business value chain. Each business function must be treated as an essential and valued contributor. All business functions must be integrated and coordinated but yet each must develop its own core capabilities. Analysis of the various slider lapper options must also include the analysis of impact to a firms manufacturing and process/equipment development infrastructure.

Dual Internal/External Focus

The primary internal focus of a manufacturing or development engineer may be on process or product sustaining issues. A manager extends beyond this internal focus by concentrating on external items that could impact her area of responsibility. In the case of slider lapping equipment development, the external focus includes upstream parties such as off-site manufacturing and downstream parties such as the electrostrictive actuator supplier. External analysis of thin film head competitors through benchmarks or reverse engineering allows quicker response to external transitions.

Continuous Improvement

As competitors continuously improve their ceramic processing techniques, so must everyone. Standing in place actually means that you are falling behind. Quality deployment principles [37] should be used in all phases of equipment development. Some of the options are more prone to the use of continuous improvement than others.

Background Information

Currently there are only two vendors that supply high-end (ELG) lapping machines to the world's ceramic electronic component manufacturers. The majority of the lap equipment is generated by the end user. This is very different from the ceramic wafer area, where large established corporations leverage their semiconductor equipment knowledge for the production of wafer processing equipment. The EC manufacturing company will be referred to as Manufacturing Company 1 or MC1, and the two equipment supply companies will be referred to as CS1 and CS2. MC1 'brainstorming' of different scenarios produced the following options for the purchase of the next generation of lap equipment:

- *Continue Internal Development on 2 Point CLL*
- *Continue Internal Development on 3 Point CLL*
- *Go fully to External Source*
- *Mix of Internal/External Sourcing*
- *Remain with Current Lapping Process*

Today's Situation

Internal Design/Manufacturing Group

MC1 has 35 internally manufactured ELG machines installed in its Shrewsbury, Louisville, Batam and Lafe facilities. The infrastructure of the equipment manufacturing group consists of 1 group leader, 1 engineer, 2 technicians, 2 machinists and 2 temporary technicians. The majority of the equipment construction is out-sourced to external suppliers. The external companies supply everything from tool bars to full machine final assemblies. The internal staff mainly focuses on equipment design and development, process improvement, and technology transfer issues.

Standard ELG Lapper

The standard internal system uses Electronic Lapping Guide (ELG) resistors for stripe height determination and control loop adjustment of bar taper. Both analog and digital ELGs are used. Bar row bow is only adjusted prior to lap. Twelve bars are lapped at the same time on three spindles; the operator interface is DOS based; the systems are networked into the local area network for database collection and product specific programming, and ramping is completed on an external machine.

CLL Lapper

The newer Closed Loop Lapper (CLL) uses the same basic components as the standard machine, but it also includes a two-point row bow closed-loop adjustment control loop. The ELG resistor readings are translated into stripe height along the bar and an algorithm computes the adjustment to apply to the bar to achieve optimal flatness. The module block is very different on the CLL process, as an electrostrictive actuator is incorporated into it for tool deflection. The CLL process is more capable than the standard process with regard to end of line throat height variance. The standard ELG lapper can be upgraded to a CLL lapper with minimal downtime and cost. Operator re-training is required as the process flow is different than the standard process.

TDL Lapper

Work is currently underway on the design of a three point deflection process called Triple Dynamic Lap (TDL). This equipment would modify the module block and tools to make use of a 3-point deflection process. As noted internally and externally, a three point adjustment should theoretically provide a more capable control process. The TDL project is currently in the design and prototype stage. The CLL lappers would be upgraded to the TDL at minimal cost. Operator training would be minimal.

External Machines

CS1 makes an ELG lapping machine specifically designed for 50% or smaller inductive/MR heads. This machine was evaluated by key MC1 lap process engineers. Similar to MC1's internal system, the CS1 system uses ELG resistors for stripe height determination and row bow corrections. Unlike the internal 12 bar system, CS1 laps one bar and requires a course lap before final lap. Row bow is corrected much more aggressively (33 times per second) than the internal machine (once every ten seconds). The machine can handle 25 resistor bonds while the internal machine is limited to 10 bond pairs. The operator interface is Windows based and Novell LAN capability is provided. Several software libraries are available including graphics, control, numerical analysis, and hardware drivers. The system uses a three point deflection tool with voice coils as the actuators. Ramping is completed on the CS1, negating the need for a separate ramp process. CS1 has been incorporated since 1985. Their annual revenue is not known as they are not listed as a private or public company in any of the library's company profile books.

The CS2 was not heavily evaluated by MC1 personal. Demonstration and literature provided by the vendor suggests a 3 bar process with stepper motor actuators. Both digital and analog

ELGs are used in the bow/taper algorithm. The CS2 also ramps the bar in a more advanced closed-loop manner. CS2 is based in Ventura California and is a subsidiary of a larger equipment supplier, which has been incorporated since 1971 and has annual revenues of $16 million.

Customer Satisfaction

Customer satisfaction is vital to the long-term success of an organization or company. Customers for the MC1 development group include Slider Manufacturing, various internal and external final assembly houses, OEM vendors, and the end user of the product. The primary customer is Slider Manufacturing in Shrewsbury, Louisville, Lafe and Batam. The extended customer base includes all of the other customers. Each of the different options represents a different scenario for customer satisfaction. Pros and Cons of each option will be discussed in this section.

Internal Development on 2/3 Point Equipment

Technology development of lapping equipment at MC1 resides in their Shrewsbury slider operation. This group has the following vision statement, goal and objectives:

Vision Statement

> *In order to remain competitive long-term in the disk drive industry, MC1 must continuously improve its slider manufacturing process capability, quality metrics, and cost.*

Goal and Objectives

Goal: *Obtain World Class Slider Lapping Performance Metrics*

Desired Objectives:
Throat Height Standard Deviation > World Class
Lap Yield > today's process
Ramp Yield => today's process
TPT <= today's process
Cost <= today's process

With regard to customer satisfaction, the internal development team should have an advantage over the external sourcing in communication, long term goal alignment, and possible cost. Communication should be enhanced with the current structure of an equipment development organization residing in one of the manufacturing areas, as long as this enhanced communication structure is properly utilized.

External Sourcing CS1/CS2

Technology development of lapping equipment at CS1 and CS2 resides in their equipment manufacturing operations. This group has input from a larger customer base than just MC1, and thus is not solely aligned with MC1's long term goals. The input from customers other than MC1 also has a positive side —diversity. Both of these external companies may have better customer relations due to the life/death situation that exists with a vendor/customer relationship (and doesn't exist with internal groups). Motivation to please a customer may be higher at these two vendors, but it has not been examined in detail.

Mix of Internal/External Sourcing

The dual option may tend to have higher customer satisfaction due to the customers ability to pick the option that adheres best to their needs. However, the maintenance and operation of two diverse processes may exasperate customers. Risk management philosophy dictates a lower risk with a larger vendor source.

Remain with Current Lapping Process

Future quality should suffer with this option as innovation will be limited. As the required strip height dimensions decrease, the current process will become less capable. The process already has had much continuous improvement, and is currently at a point where quality is built, rather than inspected, into the process.

Table 7-1. Customer satisfaction qualitative rating.

	Customer Satisfaction
Internal Development 2 Point	❽
Internal Development 3 Point	❽
External Sourcing	❽
Mix of Internal/External	❾
Remain the Same	❶

Key Success Criteria

Cost

A Net Present Value Cash Flow analysis was completed for the internal/external equipment sourcing. The only external machine analyzed was the CS1 triple-deformable lapper. This analysis was based upon the best available information at this time. Key assumptions include:

- Labor rates are correct as quoted from finance - include benefits.
- Equipment up-time and utilization are set to best known current value. This is high as compared to observed values, but it doesn't impact the equipment to equipment analysis. Not enough information is known for exact numbers to be used.
- Cost of external equipment is based upon verbal quote. No long term contract discussions have occurred. Cost of internal equipment is based upon the current method of external body builds and internal refinement.
- Rough lappers are required for use with the external fine lappers. No rough lapper is required for either CLL or internal TDL lap.
- Two ramp machines are required for every 4 internal lappers. Rampers are not required on external machines as the fine lap also does the ramp processing.
- External lappers require tools that are significantly larger and more complex (i.e. expensive) than internal equipment.
- Actuators will be treated as expense items for internal CLL and TDL operation. We currently are having a significant actuator breakage problem from early design issues and operators low on the experience curve. The issue is being worked.
- New flex prints are required for each CS1 lap. Internal machines require changes every 60 laps.
- Diamond slurry usage is directly dependent on machine lap rate and number of machines, not on the number of bars..
- Revenue generation is a function of slider output. Slider output is a function of yield increase above the standard process. The values shown are based upon a MR yield analysis of internal CLL and standard process and external CS1 processing.
- The future cash flow is discounted based upon a 8% interest rate. This can be changed if MC1's own internal discounted cash flow (DCF) analysis interest rate is different
- No learning curve was applied to any of the given options. This could be incorporated into the economic model if learning rates are known.

An Excel™ spreadsheet and "Solver" function was used to analyze each major option. An example of the spreadsheet is as follows:

CELL CONVERSION COST BASED ON RAW SLIDER INPUT PER QUARTER

		New TDL Capital Equipment	New TDL Capital Equipment	Existing ELG Capital Equipment	New Capital Equipment	Q TDL Capital Equipment
Sliders Cell	Sliders per QTR per cell					
	Sliders per Row					
	Rows per hour					
Lappers Needed	Fine Lap Rows per Hour					
	Uptime					
	Utilization					
	Number of Fine Lappers					
	Number of Ramp Lappers					
	Rough Lappers/Fine Lap					
	Number of Rough Lappers					
Cost of Capital	Cost of each Fine Lap	$ -	$ -	$ -	$ -	$ -
	Total Cost Fine Lap	$ -	$ -	$ -	$ -	$ -
	Cost of each Rough Lap	$ -	$ -	$ -	$ -	$ -
	Cost of Rough Lap	$ -	$ -	$ -	$ -	$ -
	Grinding	$ -	$ -	$ -	$ -	$ -
	Debond	$ -	$ -	$ -	$ -	$ -
	Reconditioning	$ -	$ -	$ -	$ -	$ -
	Row Tools @ 1200/year	$ -	$ -	$ -	$ -	$ -
	Lap Plates	$ -	$ -	$ -	$ -	$ -
	Bonding Fixtures @ 250/year	$ -	$ -	$ -	$ -	$ -
	Wire Bonder	$ -	$ -	$ -	$ -	$ -
	Ramp Machines	$ -	$ -	$ -	$ -	$ -
	Net Inititial Investment	$ -	$ -	$ -	$ -	$ -
Yearly Expense Cost	Row Tools @ 200/year	$ -	$ -	$ -	$ -	$ -
	Actuators	$ -	$ -	$ -	$ -	$ -
	Flex Prints	$ -	$ -	$ -	$ -	$ -
	Diamond Slurry	$ -	$ -	$ -	$ -	$ -
	Lap Plates	$ -	$ -	$ -	$ -	$ -
	Yearly Tool Expense Cost	$ -	$ -	$ -	$ -	$ -
Yearly Facility Cost	Fine Lapper Floor Space sq ft	0	0	0	0	0
	Rough Lapper Floor Space sq ft	0	0	0	0	0
	Ramp Lapper Floor Space sq ft	0	0	0	0	0
	cost /sq foot/month	$ -	$ -	$ -	$ -	$ -
	Yearly Facility Cost	$ -	$ -	$ -	$ -	$ -
Labor Cost/Year	Direct Labor Hours/week	0	0	0	0	0
	Direct Labor Hourly Wage + Benefits	$ -	$ -	$ -	$ -	$ -
	In-Direct Labor Hours/week	0	0	0	0	0
	In-Direct Labor Wage + Benefits	$ -	$ -	$ -	$ -	$ -
	Yearly Labor Cost	$ -	$ -	$ -	$ -	$ -
	Total Yearly Costs	$ -	$ -	$ -	$ -	$ -
	Change in Yearly Cost	$ -	$ -	$ -	$ -	$ -
Recurring Cash Flow	Revenue generated per slider	$ -	$ -	$ -	$ -	$ -
	Current Slider Yield					
	Yield Year 1					
	Yield Year 2					
	Yield Year 3					
	Yield Year 4					
	Yield Year 5					
	Overall Slider Area Yield					
	Yield Improvement Slider Output					
	Extra Slider Output Year 1					
	EXtra Slider Output Year 2					
	Extra Slider Output Year 3					
	Extra Slider Output Year 4					
	Extra Slider Output Year 5					
	Discounted Cash Flow					
	PV Cash Flow Year 1	$ -	$ -	$ -	$ -	$ -
	PV Cash Flow Year 2	$ -	$ -	$ -	$ -	$ -
	PV Cash Flow Year 3	$ -	$ -	$ -	$ -	$ -
	PV Cash Flow Year 4	$ -	$ -	$ -	$ -	$ -
	PV Cash Flow Year 5	$ -	$ -	$ -	$ -	$ -
	Extra Recurring Cash Flow	$ -	$ -	$ -	$ -	$ -
Net Present Cash Flow	*Investment -ECRF*	$ -	$ -	$ -	$ -	$ -

Figure 7-1. Net present value analysis of equipment purchase options.

Internal Development on 2/3 Point Equipment

The internal triple dynamic deformable development option showed the largest Net Present Cash Value of any of the options studied, based upon the given assumptions. The 2-point

CLL option also had good NPCV even with model yields that are lower than what can be expected (learning curve effects). The key driver for both of these options is that the lapper can process 12 bars at a time, while the external machines process 1 bar at a time. Yearly actuator replacement expense of 1000 units was forecast; this may decrease if stainless steel support structures work as designed.

External Sourcing CS1/CS2

External equipment purchase could be justified if either the internal equipment development costs or operating expenses increase or if the technology can not be transferred in the given time-frame due to technology glitches. The analysis assumed that either a 20 or 30 minute throughput time could be obtained. The throughput of the machine as measured was 40 - 60 minutes on analogous plate materials and diamond sizes. Because of the single bar process the capital acquisition cost is very high. The yearly expense values are also very high, as the process currently requires single use of flex print. Diamond use is significantly higher due to the single lap process. No actuator loss is projected as the voice coil lifetime is not known. The CS1 lapper requires a very different tool bar, thus requiring several new fixtures. The CS1 lappers also require a rough lap process but do not require external ramp lapping.

Mix of Internal/External Sourcing

Mixing lappers would be difficult, but possible in a single cell, as the tools are very different. A better situation for mixing internal and external machines would be cell to cell mixing. This may also cause issues external to the lap cell, but this is currently occurring in Shrewsbury with the CLL and standard tools. One advantage of a mix scenario is the ability to process high end products on the cells with the best available equipment (stripe height Cpk).

Remain with Current Lapping Process

Capital acquisition costs are low, and yearly expense costs are low, but recurring cash flow is zero. As the product tolerances decrease, the yield of the current lap process will decrease. The other options are more economically feasible.

Quality

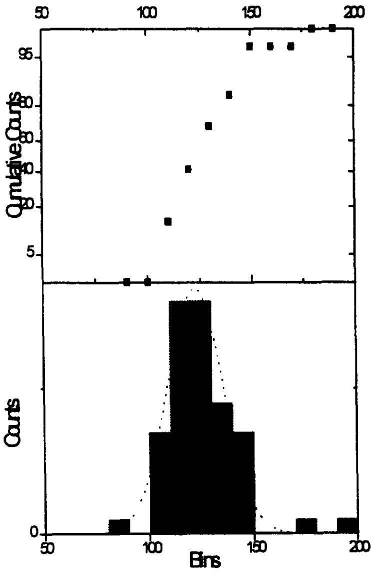
Stripe Height Standard Deviation

Slider lap is a key process step in the processing of a recording head, as this process step determines throat height (inductive heads) and stripe height (magneto-resistive heads). Variance associated with this step directly impacts outgoing customer variance. In-line and end-of-line throat height process capability (Cpk) should exceed 1.0 for 50% product. Pico product (30%) poses even greater process challenges.

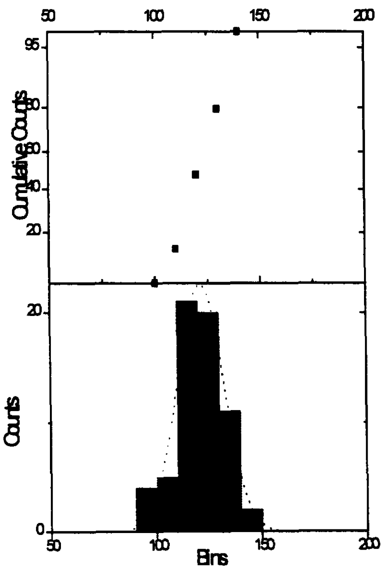
Because of the use of Electrical Lapping Guides (ELG), stripe height mean is easily obtained. The product is lapped until a bars mean value is equal to the product's target value. The variance around this mean value is the larger concern, thus making standard deviation the primary quality metric.

A paired analysis of MR stripe height was completed by the external equipment evaluation team. This analysis showed the following results:

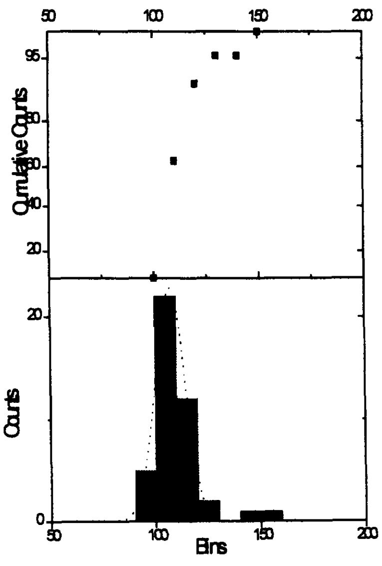
Standard ELG



CLL ELG



TDL ELG



The external analysis team analyzed the MR stripe height distribution produced by each of the three lapping processes. The TDL ELG process was run by engineers while the standard

ELG and CLL ELG processes were run in normal production mode. Is has been demonstrated that the CLL process has a standard deviation of between 1x and 1.6x higher in high volume manufactoring; this disparity is under scrutiny.

Table 7-2. Product stripe height specification vs. volume production.

Product	*Normalized Specification*[i]	*Mass Production Start Date*
A	*+/- 0.60*	*Jan '96*
B	*+/- 0.60*	*Dec '96*
C	*+/- 0.51*	*May '97*
D	*+/- 0.40*	*Jan '98*

The stripe height distribution was altered with hard limits in order to simulate an end-of-line quality test and yield loss. These yields were used in the economic analysis based upon the high/low limits[ii] and product introduction time-frame.

Table 7-3. Normalized throat height standard deviation vs. normalized bin limit

	All Data	*+/- 1.0 Spec*	*+/-0.60 Spec*	*+/- 0.51 Spec*	*+/- 0.40 Spec*
Standard ELG	*1.00*	*0.71*	*0.57*	*0.53*	*0.40*
CLL ELG	*0.64*	*0.64*	*0.51*	*0.43*	*0.42*
TDL ELG	*0.70*	*0.38*	*0.38*	*0.34*	*0.30*

The production start date, and lapping process standard deviation will vary from the above forecasts. The standard deviation of all three lapping processes will be smaller than what is shown, as operators will progress along the learning curve, and innovation will occur in the process/equipment.

Table 7-4. Normalized throat height process yield vs. normalized bin limit.

	+/- 1.0 Spec	*+/- 0.60 Spec*	*+/- 0.51 Spec*	*+/- 0.40 Spec*
Standard ELG	*1.00*	*0.84*	*0.77*	*0.57*
CLL ELG	*1.06*	*0.95*	*0.87*	*0.84*
TDL ELG	*1.00*	*1.00*	*0.98*	*0.92*

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[i] Normalized to current product +/- specification = 1.00

[ii] The product specifications have been normalized in order to preserve confidential information.

The process yield was calculated by process engineering and is based upon the measured stripe height variance and the expected process window. The process window is defined by the future product introduction date.

Time to Market (TTM)

As the slider line is currently designed, the lapping process is the process bottleneck operation. The lapping process is also one of the highest sources of yield loss. Any improvement in the lapper directly impacts manufacturing's quality and cost structure. The time it takes to successfully bring a new lapper or lapping process on-line, perform characterization, implement it into production, and transfer it to other sites is significant. The time it takes to incrementally improve a lapper also impacts manufacturing, as existing equipment problem resolution time in minimized.

Internal Development on 2/3 Point Equipment

The internal 2/3 point development option has longer time to market than the external option since internal development is not yet complete. Several key obstacles need to be overcome before the triple dynamic lap process is ready for production. The CLL process is the only option already in volume production, and thus has started its secondary learning curve (primary in development stage, secondary in production). Major issues impacting CLL are production refinement issues of actuator cracking, ramp process capability, and operator training. Any learnings of the CLL should positively impact the learning curve of the internal TDL. The existing equipment problem resolution time in Shrewsbury is very good with the internal equipment, as the infrastructure is already there and has progressed far on the equipment learning curve. This may not be the case in Lafe or Batam, as their maintenance and engineering staff has had minimal exposure to the equipment set.

Running the same equipment set at several sites (Batam, Lafe, Shrewsbury, Louisville) allows knowledge transfer and a faster learning rate, if systems are in place for this knowledge transfer. Problem task forces, process change control boards, engineering rotations, extended relationships and other methods are used for cross-site knowledge transfer.

External Sourcing

The external equipment TTM is good as the equipment set is already defined, is functional and can be purchased in quantity. Delivery schedule is currently 18 weeks after purchase order processing, with capacity limited to 5 machines per week. The throat height metrics produced by the equipment are currently superior. The equipment throughput is inferior. The time to resolve problems with equipment changes is unknown - this will depend on the engineering infrastructure of the vendor and the communication mode between MC1 and the vendor.

Mix of Internal/External Sourcing

A mix of internal and external would leverage the time to market of each equipment set. If the external equipment is ready for volume production before the internal equipment, then product release schedules would not be negatively impacted by slow internal development. Major problems with existing equipment could still be resolved by the existing infrastructure. Innovations in external equipment design that are spawned by other users could quickly be incorporated into the process as the learning curve on external equipment use would already show progression.

Remain with Current Lapping Process (Do Nothing)

Time to market is nonexistent, as the equipment is already used in large scale production.

Innovation

Innovation goes beyond incremental changes. True innovations result in dramatic product improvement or cost savings. An environment can exist where both innovations and continuous improvements are obtained. A continuous flow of innovations is required if MC1 is to achieve and maintain world class slider manufacturing status. Equipment innovation is dependent on ease of change and user/producer core capabilities.

Internal Development on 2/3 Point Equipment

Internal innovations are driven by need and by stretch development. Needs are defined by the customer, manufacturing, while stretch development occurs in organizations as a function of management steering. An example of a need is the customers requirement of high throughput. Resolution of that need is the multi-lapper innovation that occurred with the initial ELG lapper. Continuous improvement issues are more along the line of signal to noise ratio improvements through better bonding techniques.

Stretch development innovation capability in the current MC1 T&E equipment development infrastructure appears to be adequate. The organization is pushed to try things in different ways. Daily status meetings also serve as problem brainstorming meetings in which both continuous improvement and true innovations are discussed.

External Sourcing CS1/CS2

The innovation ability of the two vendors is not known, as a long term relationship has not been present. Equipment innovation may be stronger at the external firm, due to consistent focus on this single product. The internal development team also has sustaining responsibilities in other slider areas. The innovation of the external firm may also be less, as small firm cash flow issues dictates a low level of serious long-term research and development.

If the vendor was a major supplier to another magnetic head manufacturer, then MC1 could leverage shared learning's of the firm. This happens in semiconductor equipment firms, as many major breakthrough in wafer processing are transferred from company to company through the equipment vendor. CS1 has another large customer, so some leverage is present.

Mix of Internal/External Sourcing

A likely scenario of mix lapper sourcing is that innovations of the external machine may be easily understood and applied to the internal machine. For this to occur, the external machines must be located near the development team of the internal machines. If the external machines are located in Lafe, then little innovation transfer will occur with the internal development team.

On the negative side, CS1 or CS2 may gain significant leverage from learning MC1's innovations, and extend these innovation to their full customer base. Control algorithm, multiple bar processing, and actuator technology are all key areas with potential innovation transfer.

Remain with Current Lapping Process (Do Nothing)

No major innovation would occur if the decision is made to stay with the current equipment and not improve it. Continuous improvement may occur from the operator level, but if the internal development team is disbanded, no engineering innovations would happen.

Table 7-5. Ranking of key metrics by equipment sourcing strategy.

	Cost	*Quality*	*TTM*	*Innovation*
Internal Development 2 Point	❽	❼	❽	❽
Internal Development 3 Point	❾	❽	❺	❽
External Sourcing	❻	❾	❼	❼
Mix of Internal/External	❺	❾	❻	❾
Remain the Same	❶	❶	❾	❶

Value Chain Analysis

The slider lap process is an essential and valued contributor to MC1's disk drive value chain. By retaining a core competence in lapping and lap technology, the slider operation provides competitive technological and economic value to MC1. The lap design and procurement function is indeed integrated into the slider business.

Internal Development on 2/3 Point Equipment

The core capabilities of the lapper design team extends beyond machine procurement activities, as this team is also a key contributor to manufacturing problem resolution teams. The team also provides any necessary hardware and software upgrades to the existing machine set.

External Sourcing CS1/CS2

If the internal development is not providing at least a market value to the processing of magnetic heads, then MC1 should disband the internal team and go with external sourcing. If the internal development team adds value, then it should remain, and provide further value to each new technology. Full external equipment sourcing is a go/no go decision. Going to full external sourcing will significantly diminish the value of an internal team, and will result in the core competencies of this team being lost. If the internal team was disbanded, an internal infrastructure would need to be created to resolve equipment problems on both the new and old equipment.

Alternatively, the core competencies of the external vendor may be gained. MC1 is not in the business of equipment manufacturing: it is in the business of hard drive design and manufacturing. If the core competencies of the external vendor(s) add higher value to MC1 than the internal team, then the external sourcing should be considered. At this moment it is not thought that either vendor provides significantly more value than the internal sourcing.

Mix of Internal/External Sourcing

Mixing of internal and external sourcing may actually hurt the value chain, as manufacturing needs to focus on two different types of equipment to sustain and improve. Each slider area has limited resources, and creating a multi vendor supply chain may encumber those resources.

Remain with Current Lapping Process (Do Nothing)

The current lapping process provides significant value to the slider area, but the concern is adequate future process capability. As the size of heads shrink, and the required throat height and MR stripe height shrink, the required variance control increases. The value of the current process and equipment set degrades with time.

Table 7-6. Ranking of value chain contribution vs. equipment source.

	Value Chain Contribution
Internal Development 2 Point	❼
Internal Development 3 Point	❽
External Sourcing	❻
Mix of Internal/External	❼
Remain the Same	❸

Dual Internal/External Focus

Both internal and external focus is needed for successful technology management. The primary focus of a manufacturing engineer is on process sustaining or new product implementation in the process. A manager extends beyond this internal focus by concentrating on external items that could impact their area of responsibility. In the case of slider lapping equipment development, the external focus includes upstream parties such as Batam manufacturing and downstream parties such as the electrostrictive actuator supplier. External analysis of thin film head competitors through benchmarks or reverse engineering allows the manager to respond quicker to external transitions. Each of the following options has its own impact on both the internal and external focus of the development group.

Internal Development on 2/3 Point Equipment

Internal focus would be enhanced while external focus may be minimized with the sole internal sourcing option. The internal team may become so focused on day to day sustaining issues that the more global external focus is minimized. It may be possible for the manager to maintain both an internal and external focus while the people under him/her are focused on the key internal items. The internal focus remains strong with the internal equipment design infrastructure in place, as this group should know the pulse of the manufacturing sector (customer needs).

External Sourcing CS1/CS2

External focus becomes larger, as the vendor itself is part of the external world. Internal focus may become minimized, as the equipment set is not manufactured solely for the internal customers requirements. The external vendors focus into the internal customer requirements is diluted by customer/vendor disclosure agreements.

Mix of Internal/External Sourcing

By having both an internal and an external equipment supplier, the focus extends to both areas. An external focus may provide information on competitor lap direction changes, as changes in the external equipment are noticed. If the vendor builds equipment only to the specific needs of a specific customer, then the external focus is not enhanced. Analysis of external equipment at trade shows may provide just as much information on competitor direction changes as actually obtaining the external equipment set.

Remain with Current Lapping Process (Do Nothing)

Focus in solely on internal sustaining with little external focus.

Table 7-7. Ranking of internal/external focus vs. equipment source.

	Internal/External Focus
Internal Development 2 Point	❻
Internal Development 3 Point	❻
External Sourcing	❺
Mix of Internal/External	❽
Remain the Same	❶

Continuous Improvement

Continuous improvement of either a slider lap process or a lapper is contingent upon the infrastructure having adequate problem knowledge and the ability to act upon that knowledge. As recording head density continuously increases, MC1 needs to continuously improve slider processing techniques. Staying in place actually means that you are falling behind. Both internal and external equipment may have continuous improvement, but the learning curves may be different due to communication and reticent agreements..

Internal Development on 2/3 Point Equipment

The Technology & Engineering group has a strong link with the manufacturing floor - this in turn influences the direction of next generation equipment design. Organizationally the group is separate from the Manufacturing Engineering group, but in the past it has been part of the Manufacturing group. The impact of having extremely close ties with manufacturing is three fold:

1)Technology transfer is locally robust.
2) Design changes are incremental and continuous.
3) Communication concerning customer needs is high.

Quick and accurate technology transfer is vital in the hard drive industry as design cycles can be as short as 18 months. Running the new technology with true production quantity brings out capability issues that would not be found in the pilot line mode or operation. The close tie with manufacturing minimizes an "over the wall" type technology transfer. A negative of the close tie with local manufacturing is that the remote technology transfer ability to other internal sites was not characterized during this time period due to local incremental improvements.

The incremental design improvement methodology has both merit and fault. Incremental changes are made quickly and at low cost. Usually the incremental changes are based on valid customer concerns. Its negatives include constrained innovation, and possible incorrect strategic direction.

The close tie with manufacturing allows the design and development group to maintain an active link with the customers, and provides agility in manufacturing problem analysis and resolution. A negative is that developmental efforts may be weakened due to resource dilution. If the manufacturing infrastructure is not self-supporting in new process and equipment maintenance, then the development groups resources will be tapped.

External Sourcing CS1/CS2

External vendors continuously improve, based upon their own abilities and their customers willingness to share information. It is more difficult for an external vendor to complete operator interaction analysis, and thus the input from the primary user of the equipment requires translation through internal engineering. Vendors may have better engineering analysis and design abilities, dependent upon their infrastructure. The CS1 infrastructure appears to be similar to the MC1 equipment infrastructure. The CS2 infrastructure in not fully known.

Mix of Internal/External Sourcing

Similar to innovation analysis, purchase of an external equipment set may lead to continuous improvement gains. If the correct personnel are involved in the internal evaluation of the external equipment, then a benchmark situation exists. External sourcing may dilute the internal equipment's continuous improvements, as resources are thinned.

Remain with Current Lapping Process (Do Nothing)

Continuous improvement does occur with the current lappers, but the majority of the improvement is from the development infrastructure. If this infrastructure is removed, then continuous improvement is expected to decrease.

Table 7-8. Ranking of continuous improvement vs. equipment source.

	Continuous Improvement
Internal Development 2 Point	❽
Internal Development 3 Point	❼
External Sourcing	❹
Mix of Internal/External	❻
Remain the Same	❶

Other Factors

Throughput

Throughput has been a major influence in the design of the internal ELG lappers due to the local manufacturing mentality. The ability of a system to many bars at a time is a major throughput enhancement. Negatives appear to be minimized with the current design, as each bar still maintains a separate feedback and control system for throat height and bow adjustment. The complexity of the machine is greatly increased by having the ability to lap multiple bars, but most of the complexity is redundant.

A concern with a primary focus on throughput is the dilution of effort on variance reduction and in-situ ramping. This may in fact not be the case for variance reduction, as the previous high throughput equipment ability allows resource direction to variance reduction. A focus on ramps has not occurred due to the simplicity and high yield of the current ramping process. But the lack of an in-situ ramp process has dictated the use of an innovative actuator. An electrostrictive actuator was needed as this is the only actuator type to hold its position once a controlling voltage is removed.

A future focus will be on in-situ ramping and non-lapped ramps, so as to minimize actuator discharge occurrences. The two external machines have in-situ ramping capability, as this is required by their use of stepper motors and voice coils for deflection actuators.

Cost As a Key Driver

The true cost of equipment does not consist purely of capital equipment depreciation. A machines footprint dictates facilitization expenses. Maintenance costs include electrical, gases, exhaust, etc. Personal expenses include training, operator assistance, preventative maintenance costs. Other expenses include spare parts, consumables. What is not usually factored in is the cost of quality. Quality costs include defects escaping the end-of-line testers and loss of face with key external customers.

Technology Transfer to Asia

As with any competitive environment, there are advantages and disadvantages with subcontracting a portion or your value chain to an external vendor. Many recent high technology agreements have failed, as once the vendor became self- sufficient they transitioned from a comrade to a competitor. A long-term risk assessment must be made with regard to transferring key corporate manufacturing technology to Asia.

Slider Lap Alternative Option Analysis

Obviously if one option could achieve all of the previously stated objectives then it would merit a recommendation. If no option meets all of the above objectives, a "best" choice option must be made. Each of the primary options will be discussed in detail.

Option 1: Continue Internal 2 Point Design/Development

This option assumes that the current infrastructure is kept in place or enhanced, and that the external machine does not dilute resources. This option further assumes that existing equipment will be the platform for continuous improvement. This option is already in production implementation phase but needs enhancement.

Advantages

Existing Infrastructure
Lapper Can be a Competitive Advantage
Use of Current 12 bar Platform
Fast Production Learning
Current Process is Incapable
Development is 80% Complete
Pico is only Months Away

Disadvantages

Requires an Internal Infrastructure
Problem if Wrong Path Pursued
Dilutes 3 Point Effort
External Ramp Required

Option 2: Continue Internal 3 Point

This option also assumes that the current infrastructure is kept in place or enhanced, and that the external machine does not dilute resources. This option further assumes that existing equipment (2 point CLL ELG) will be the platform for continuous improvement. This option is in the initial design stage.

Advantages

Existing Infrastructure
Lapper Can be a Competitive Advantage
Use of Current 12 bar Platform
Fast Production Learning
Pico is only Months Away

Disadvantages

Requires an Internal Infrastructure
Problem if Wrong Path Pursued
Dilutes 2 Point Effort
Success Risk

Option 3: External Lap Source

This option also assumes that the current development infrastructure is not required as the external vendor is present. A new infrastructure would need to be established for the installation, upkeep and continuous improvement of the new machine. Production would face a harsher learning curve, as there would exist no prior experience with this machine. The single bar lapper would require many more lappers due to throughput issues. Standard deviation would be significantly better than the current process. Capital expenditures beyond the lapper cost would be new fixtures, and tools. Expense cost increases significantly due to higher diamond and flexprint costs. Various customer/supplier communication issues extend beyond the present situation. Current equipment platforms are treated as sunk costs, as previous capital equipment decisions should not dictate future decisions. This option is in the external evaluation stage.

Advantages

No Internal Design Infrastructure Required
Standard Deviations are Better
Ramp Included
Vendor Focus is Solely Equipment Development

Disadvantages

Requires an New Sustaining Infrastructure
Internal Competitive Advantage is Lost
Dilutes 2 Point Effort
Single Bar Lap
Production Learning Curve

Option 4: Internal & External Source

This option assumes that the current infrastructure is kept in place or enhanced to include the external machine sourcing. This option further assumes that existing equipment (2/3 point CLL ELG) will be the platform for continuous improvement and that the external equipment is initially located where the internal design infrastructure has access to it. This option allows cell to cell variance based on the lapper, but this also causes extraneous processing issues to the slider area (different tool sets, etc.). Economically this option is expensive, but it is also risk adverse. This option is in the initial analysis stage.

Advantages

Risk Aversion
External Lapper may Provide Innovation for Internal Lapper
Use of Current 12 bar Platform for TPT and External for Low Sigma
Existing Capital is Utilized
Pico is only Months Away

Disadvantages

Requires an Internal Infrastructure
External Vendor may Gain Internal Innovations

Dilutes 2/3 Point Effort

Option 5: Remain Same Option

This option is the low cost option, but it is also the low improvement option. This option should be considered if the future does not require significant improvement, such as an end-of-life build out.

Advantages

Lowest Cost Option
No Production Learning Required
Existing Capital is Utilized

Disadvantages

Long-term Competitiveness is Low
Innovation
Quality Metrics are Poor
Stand in Place while the World Moves

Table 7-9. Summary of quantitative and qualitative analysis.

Option	Customer Satisfaction	Cost	Quality	Time to Market	Innovation	Value Chain	Internal/External Focs	Continuous Improvemen	Total	Average
Internal 2 Point	8	8	7	8	8	7	6	8	60	**7.5**
Internal 3 Point	8	9	8	5	8	8	6	7	59	**7.4**
External	8	6	9	7	7	6	5	4	52	**6.5**
Mix	9	5	9	6	9	7	8	6	59	**7.4**
Stay Same	1	1	1	9	1	3	1	1	18	**2.3**

Recommendations

Based upon the analysis of customer satisfaction, cost, quality, time to market, innovation, value chain impact, internal/external focus, and continuous improvement, it is recommended that MC1 continue on its path of internal development of 2 and 3 point closed loop lappers. It is also recommended that one external machine (CS1) be purchased and further evaluated by the design and development team.

An economist is an expert who will know tomorrow why the things he predicted yesterday didn't happen today.

Laurence J. Peter

Prediction is very difficult, especially about the future.
Niels Bohr

Chapter 8: Future Trends & Recommendations

Numerous successful past improvements foretell abundant future change in lapping equipment, people, and process/procedures. Product life cycles are becoming shorter, so the company must respond with a combination of continuous improvement and innovation. Each manufacturing area requires continuous improvement if the company is to remain successful in the future. Key engineering metrics, such as throat height variance, will require increasingly tighter process control with every new product generation. Both the manufacturing and the engineering design groups must become true learning organizations in order to maintain their competitiveness in the global market.

Equipment

Tool Design

Significant throat height variability reduction is possible with an increase in bending positions [94] for ceramic row lapping. Three position deflection allows the correction of a wider variety of shapes [84] than the current two deflection points and should be pursued. Several innovative 3-point tool designs were characterized in the later part of the internship, with a design similar to Figure 8-1 having promising results.

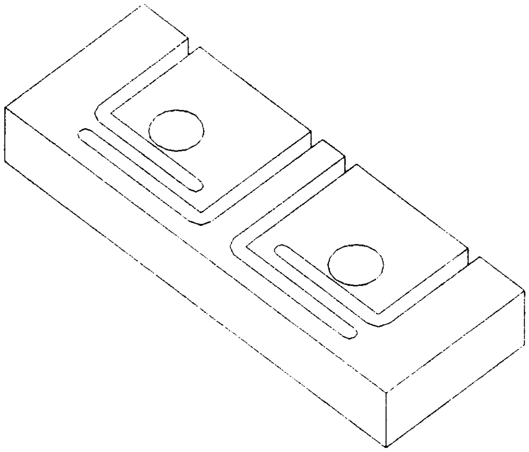

Figure 8-1. Three position transfer tool.

Finite Element Analysis (FEA) software [92] was purchased for tool design analysis and improvement. Use of this software will improve the quality of future multi-bending position designs. The software allows tool surface deflection to be modeled versus changes in materials or design. The FEA software should significantly decrease the design iteration cycle time, as prototype tool and testing cycle is fairly long.

Actuator Improvements

The relationship with the actuator vendor should be maintained, as this vendor has very high quality standards, and is open to future re-design work. Benchmark analysis of other actuator vendors should continue, as any improvement in displacement would increase process capability.

Many new types of actuators and ceramic materials are under development, with some materials showing strain values as high as 0.8%, which is an order of magnitude higher than the current PMN material. Cross [14,16] and Uchino [50] are evaluating lead zirconate stannate titanate (PZSnT) ceramics with additions of either lanthanum or niobium. These materials exhibit large strains due to the transition between the antiferroelectric and ferroelectric state, but switching fatigue is an issue [15]. Off-line lap ramp would not be compatible with these materials, as they are piezoceramics.

Improved Holding Block Design

A three-point deflection tool requires a three actuator holding block, so the equipment design team is re-designing the holding block with two different styles. A 'linear' style block allows direct linkage of the electrostrictive actuator components to the row tool. A mechanical amplification style block, as shown in Figure 8-2, uses lever arms to increase actuator deflection, but force is decreased proportionately.

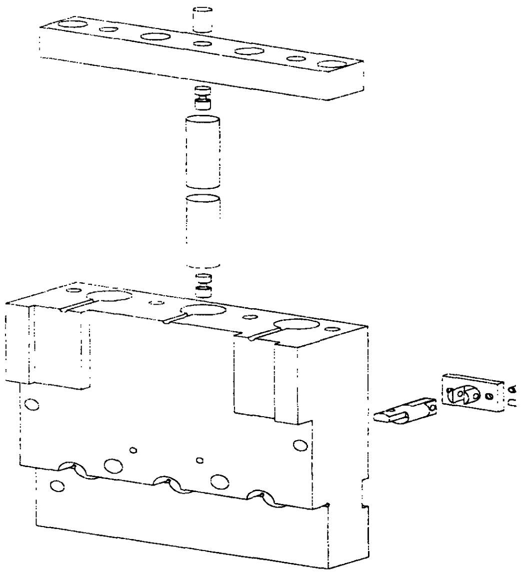

Figure 8-2. Example of 3 position holding block.

In order for the closed loop process to achieve a capability (Cpk) greater than 1.2, the row deflection must be increased. If the same type of actuators are to be used, the additional deflection must come from other areas of improvement, such as mechanical amplification or reduction in linkage loss.

A holding block with a mechanical amplification lever arm is shown in Figure 8-3. Upon testing, this design did not fully meet the desired design characteristics of triple amplification, but it did increase the design team's knowledge of component interactions. This design was innovative in that it was not merely a simple redesign of an existing holding block, but it incorporated several new features that were learned from external benchmarks. In future designs, these interactions should be factored in.

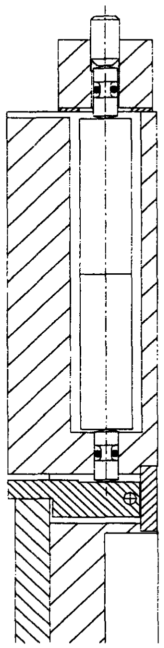

Figure 8-3. Dual actuator triple amplification block.

Similar to tool design, the use of FEA software should increase the speed of the holding block development design cycle and allow the analysis of tool, actuator and block interaction. Incorporation of novel displacement amplification devices, such as flextensional "moonies", increase stroke but decrease the applied force. Newnham et al [49] designed moonie actuators with 20x higher displacement values, and had good correlation between FEA and experimental results. Thirupathi [66] used a stacked biomorph design to obtain high displacement along with high force.

Process Improvement

In-Situ Ramp

Development of either an in-situ lap ramp process or an alternative ramp process would improve the design flexibility of the current lap equipment. Higher displacement actuators could be used instead of PMN electrostrictive actuators. Discharging errors would be eliminated.

Data Collection

Most of the information technology systems are in place for world class data collection and analysis, but several key pieces are missing. The manufacturing organization's fear of a "big brother" environment should not disallow the use of operator coding in the database. Future improvement will require operators to be trained correctly and to learn from their mistakes. Simply ignoring the impact of operator variation means that one of the largest process capability improvements is being ignored.

The engineering data collection system is of high quality, but the user data analysis software is poor. Dedication of a future process or software engineer to the task of making easy to use process analysis software tools would remove some boulders from the process engineer's and manufacturing technician's learning curve.

Benchmark Activities

Both internal and external benchmarking of process activities should enhance future process capability. External equipment analysis should include process flow analysis. Internal process control techniques of the wafer fab should be compared and contrasted.

Process Change Control

In a quickly changing environment it is easy to ignore practices such as documenting and controlling manufacturing process changes. The documentation of process experiments and changes improves facilitates future learning when things don't work out as planned. What is perceived as a time waste may actually save time in the future by keeping the "firefighting" of non-robust changes down to a minimum level. In a process as complicated as this one there is bound to be interactions among the various processing steps; discussion of the changes in an organized manner allows many interactions to be understood before the interactions impact the floor. Variation analysis of equipment or processes is greatly confounded when several different process control operating software revisions are present. Automated in-line statistical process control (SPC) trending of key engineering or equipment metrics would aide quick problem resolution. Documentation of major process changes would force statistical analysis of the change on the manufacturing line.

People Improvement

People are the most valuable asset of an organization. It is vital that people receive training applicable to their area of responsibility and increase their problem resolution skills. Many of the Kaizen [37] or TQM [61] procedures were successful during the internship. Fishbone generation, brainstorming, the "5 whys", and PDCA experimentation all yielded satisfactory results. In the future of empowered work forces, the front-line production operator needs these skills if the process is to continuously improve. Several operators enjoyed the experience of having their ideas listened to; this needs to continue. An incentive system which rewards quality improvement in addition to quantity or throughput would relieve some of the manufacturing/engineering animosity that is present.

Problem resolution and data analysis skill need improvement throughout the organization. There does not appear to be formal training or guidelines in problem resolution techniques. A systems solution would be formal training and implementation of a best known problem resolution methodology; the 7 step method [61] would be a good starting point.

> *More than any time in history mankind faces a crossroads. One path leads to despair and utter hopelessness, the other to total extinction. Let us pray that we have the wisdom to choose correctly.*
>
> Woody Allen

...The next one." -- When asked which was his favorite project.
Frank Lloyd Wright

Chapter 9: Conclusion

A closed-loop ceramic lapping process was characterized, modified, and implemented in a high volume manufacturing line. Closed-loop lapping significantly improved the flatness control of a $TiC\text{-}Al_2O_3$ ceramic lap process for both in-line and end-of-line monitors.

Electrostrictive ceramic actuators were used to adjust ceramic row deflection during the closed-loop lap process. Use of these innovative electrostrictive actuators in a high volume production line resulted in many early design and operational problems; these problems were resolved with standard TQM analysis techniques and plan-do-check-act cycles.

The engineering staff of the sponsoring company was very supportive during the entire internship. Designing and machining of various mechanical fixtures was always accomplished quickly and with high quality. During the 6.5 month internship, several engineering and manufacturing opportunities came to light. Resolution of these opportunities provided significant insight into the interaction of process design, equipment design, process implementation and high volume manufacturing.

I don't know why I did it, I don't know why I enjoyed it, and I don't know why I'll do it again.
Bart Simpson

I find that a great part of the information I have was acquired by looking up something and finding something else on the way.

Franklin P. Adams

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> *Knowledge is of two kinds. We know a subject ourselves, or we know where we can find information on it.*
>
> *Samuel Johnson*

> *The secret to creativity is knowing how to hide your sources.*
>
> Albert Einstein

Attachment 1

System Dynamics Variable Description

Equations used in the Chapter 4 simulation are described below. The format is equation number, equation, units, and general description. Please see chapter 4 for a detailed description of the model.

(01) Actuator Area = 3.1415*(Actuator Diameter/2)^2
Units: inch squared
Calculation of actuator area.

(02) Actuator Diameter = 0.25
Units: inch
Standard electrostrictive multistack actuator diameter is 1/4 inch.

(03) Actuator E = 8.84e+006
Units: psi
The modulus of elasticity for the actuator was calculated from vendor data. The actuator is a PMN multi-stack (150 layers) electrostrictive ceramic.

(04) Actuator Elongation =(1e-006*(-297.916+21.562*Voltage-0.0734*Voltage^2)+0.000277)/Broken Actuator
Units: inch
The elongation of the actuator as a function of applied voltage. Note in chapter 4 the curve that was used for this equation. This was generated from no load analysis of several actuators. The broken actuator variable is the "what if" for analysis of when one of the two actuators is non-functional.

(05) Actuator Elongation Loss =IF THEN ELSE(Time<90,0,Actuator Max Extension -Actuator Elongation)
Units: inch
Deflection loss after 90 cycles is equal to the Actuator Max Extension minus the Actuator Elongation. The process starts with a no-load charging of the actuators to full extension (150 volts). If the actuator is fully extended during the process the loss would be zero.

(06) Actuator K = Actuator E*Actuator Area/Actuator Length
Units: inch*psi
The spring constant of the actuator is equal to the modulus of elasticity for the actuator times the actuator area, divided by its length. This is shown as equation 4-3.

(07) Actuator Length = 1.5
Units: inch
Standard length for 2 electrostrictive actuators is 1.5 inch.

(08) Actuator Max Analysis =MAX(Actuator Max Extension,Actuator Elongation)
Units: inch
Analysis of whether the actuator max extension stock value or the actuator elongation value is bigger. This allows the stock value to modified without run time errors.

(09) Actuator Max Extension = INTEG(Change in Actuator Extention,0)
Units: inch
Stock item which increases by the delta of itself and any larger actuator extension.

(10) Actuator Ramp Time = 30

Units: cycles
Determines how fast the first part of the graph ramps up. This used for graphical demonstration of actuator elongation vs. applied voltage in the initial 30 cycles.

(11) Bonding Process Error = 1e-005
Units: inch
User input for "what if" analysis of errors in the bonding process.

(12) Broken Actuator = 1
Units: **undefined**
A value of 1 means no broken actuators, and a value of 2 means 1 broken actuator. This value is used to divide the actuator elongation -i.e. if one actuator is broken the elongation of the dual actuator stack will be cut in half.

(13) Ceramic Tip Area = Ceramic Width*Ceramic Width
Units: inch squared
Assumes a square ceramic tip.

(14) Ceramic Tip E = 1e+007
Units: psi
Ceramic tip modulus of elasticity is 10E6.

(15) Ceramic Tip K = Ceramic Tip E*Ceramic Tip Area/Ceramic Tip Length
Units: inch*psi
The spring constant of the ceramic tip is equal to its modulus of elasticity times its area divided by the tip length.

(16) Ceramic Tip Length = 0.165*2
Units: inch
The length of one ceramic tip is 0.165 inch. The value is multiplied by 2 because there are 2 tips.

(17) Ceramic Width = 0.125
Units: inch
Standard ceramic width is 0.125 inch

(18) Change in Actuator Extension = Actuator Max Analysis-Actuator Max Extension
Units: inch
The Change in Actuator Extension increases the stock Actuator_Max_Extension by the difference between the previous value and the new actuator max value. This is part of the actuator elongation sector.

(19) Change in Max = Max Analysis-Slider Max Position
Units: inch
The Change in Max increases the stock Slider_max_position by the difference between the previous value and the new slider max value. This is part of the process capabilty sector.

(20) Change in Min = 0-(Slider Min Position-Min Analysis)
Units: inch
The Change in Min decreases the stock Slider_min_position by the difference between the previous value and the new slider max value. This is part of the process capabilty sector.

(21) Change in Position = IF THEN ELSE(Time<75,Slider Target Position Gap/delay,0)
Units: inch
The Change in position increases the stock row_bow_adjustment by the difference between the previous value and the new slider target position value. This is part of the row bow adjustment sector.

(22) Computer Voltage Ramping = RAMP(5,0,Actuator Ramp Time)
Units: volts/cycle
Determines how fast to ramp up the voltage in the initial few cycles. The value of 5 allows the graphs to show the non-linear shape of actuator extension vs. voltage.

(23) DDL Cycles = 6
Units: cycles
Creates a variable for simulating the number of times the lapping process will cycle through the complete voltage range of 15 to 150 volts. (The sine wave pattern for simulation time 120 to 300).

(24) DDL Slider Position = Slider Target Position
Units: inch
DDL_slider_position is set equal to the slider_target_position variable in order to make the main graphic more readable and to break out the max/min analysis as a separate sector.

(25) DDL Voltage Cycles = IF THEN ELSE(Time<90,0,67.5+67.5*SIN(Time/DDL Cycles))
Units: undefined
Modulates the input voltage to the actuator after time=90. A random number generator can also be used, as shown in figure 4-5 in the text.

(26) delay = 2
Units: cycles
The delay is used in the row bow adjustment sector for smoothing of the change in position variable - i.e. Change in Position = IF THEN ELSE(Time<75,Slider Target Position Gap/delay,0)

(27) Desired Slider Target Position = 0.0004
Units: inch
This is the desired position of the slider after the row bow process is completed. I.e the 400 u" positive bow at 150 volts will decrease to 0 u" (flat state) once the voltage is lowered to 58 volts at the start of the lapping.

(28) FINAL TIME = 300
Units: cycles
The final time for the simulation.

(29) Full Discharge = 1
Units: **undefined**
Full discharge = 0 results in a actuator with zero charge. A setting of 1 results in full actuator charging.

(30) Initial Position = 0
Units: inch
Used in both the slider max and min stock analysis of the capability sector. The if_then_else logic requires a starting value - i.e. Slider Min Position = INTEG(IF THEN ELSE(Time>100,Change in Min,0),Initial Position).

(31) INITIAL TIME = 0
Units: cycles
The initial time for the simulation.

(32) Linkage Loss =IF THEN ELSE(Time<Linkage Loss Time,0,Linkage Loss Quantity)
Units: inch
Another "what if" variable. It was added to model to understand the impact of a linkage loss during the lap cycle, as described in the Variance and Linkage Loss sector analysis in the text.

(33) Linkage Loss Quantity = 0
Units: inch
Variable to change lap linkage losses intrinsic to mechanical linkages. Normally it is set to zero, thus assuming no linkage loss.

(34) Linkage Loss Time = 250
Units: cycles
Allows the user to specify when the linkage loss will occur. It is set to 250 in the standard analysis in order to contrast the lap process with/without linkage loss.

(35) Max Analysis = MAX(DDL Slider Position,Slider Max Position)
Units: inch
Determines whether the stock value (Slider_max_position) or the new cycle value (DDL Slider position) is larger.

(36) Min Analysis = MIN(DDL Slider Position,Slider Min Position)
Units: inch
Determines whether the stock value (Slider_min_position) or the new cycle value (DDL Slider position) is smaller.

(37) one =0.001
Units: undefined
Not used in current model.

(38) Pin Area = 3.1415*(Pin Diameter/2)^2
Units: inch squared
The area of the pin or rod used to transfer the displacement of the actuator to the beam.

(39) Pin Diameter = 0.087
Units: inch
Used to calculate the area of the pin.

(40) Pin E = 3e+007
Units: **undefined**
Pin material modulus of elasticity. Set equal to stainless steel E=30E6. Broken out as a separate variable so that the user can easily change in order to model the impact of different materials.

(41) Pin K = Pin E*Pin Area/Pin Length
Units: inch*psi
Spring constant of the pin.

(42) Pin Length = 0.48
Units: inch
Length of the pin or rod used to transfer the actuator displacement to the beam.

(43) Preset Start Value = 0.0007
Units: inch
This variable is broken out such that the user can easily change it and analyze its impact. The preset start value is the deflection that the operator physically adds to the beam before row bow measurement.

(44) Process Capability = Slider Max Position-Slider Min Position-Linkage Loss
Units: inch
Process_capability is equal to Slider_max_position minus Slider_min_position. This variable quantifies the effective range of tool position - i.e. the full capability of the process as defined by changes in other variables.

(45) Ramp Slider Position = DDL Slider Position
Units: inch
In this model Ramp_slider_position is set equal to DDL_slider_position. It was brought out as a separate variable in order to facilitate future changes to the model, such as actuator discharge.

(46) Row Bow Adjust = IF THEN ELSE(Time<50,0,Row Bow Adjustment)
Units: inch
Row_bow_adjust is set equal to the stock value of Row_bow_adjustment after 50 cycles. The model was set up this way in order for the operators process flow to be graphical shown and understood.

(47) Row Bow Adjustment = INTEG(IF THEN ELSE(Time<50,0,Change in Position), Preset Start Value)
Units: inch
Row_bow_adjustment is a stock value that is adjusted by the Change_in_position. The Preset_start_value is the defined starting point for the stock.

(48) SAVEPER = TIME STEP
Units: Month
The frequency with which output is stored.

(49) Slider Max Position = INTEG(IF THEN ELSE(Time>100,Change in Max,0),Initial Position)
Units: inch
This stock item is used to quantify the highest value achieved of the DDL slider variable. The previous value is analyzed vs. Change_in_max (which is simply the delta of the current value and the previous value) after 100 cycles. Slider_max_position minus Slider_min_position is equal to the Process_capability.

(50) Slider Min Position = INTEG(IF THEN ELSE(Time>100,Change in Min,0),Initial Position)
Units: inch
This stock item is used to quantify the lowest value achieved of the DDL_slider variable. The previous value is analyzed vs. Change_in_min, (which is simply the delta of the current value and the previous value) after 100 cycles. Slider_max_position minus Slider_min_position is equal to the Process_capability.

(51) Slider Target Position = Tool Position+Bonding Process Error
Units: inch
Slider_target_position is equal to the tool_position plus the bonding_process_error. The tool_position is determined by the elongation or deflection of the tool minus the linkage loss and the flatness built into the tool. The input variables can be modulated to associate variance with the tool position.

(52) Slider Target Position Gap = Desired Slider Target Position-Slider Target Position
Units: inch
The Slider_Target_Position_Gap is the variable at the heart of this models gap analysis and recovery. In the process the operator would know the Desired Slider Target Position by specification and measure the Slider Target Position on the Row Bow operation, and make an adjustment to lower the gap.

(53) System Force = MAX(System K*(Row Bow Adjust-Actuator Elongation Loss),0)
Units: psi
The system_force variable is the force at the pin/beam interface. Positive deflection requires larger force. The force is equal to the system spring constant multiplied by the deflection of the beam (row bow adjust - actuator loss). The actuator loss is the Actuator Max Extension minus Actuator Elongation. Thus an increase in the Preset start value results in a higher row bow adjust, which results in a higher force due to futher extension of the beam.

(54) System K = 1/(1/Actuator K+1/Ceramic Tip K+1/Pin K+1/Tool K)
Units: psi*inch

System Spring Constant is quantified with component spring constants

(55) TIME STEP = 0.5
Units: Month
The time step for the simulation.

(56) Tool Cut Depth = 0.1927
Units: inch
The tool cut depth is essentially the beam thickness. Value input by user.

(57) Tool Cut Length = 0.632
Units: inch
The tool cut length is essentially the beam length. Value input by user.

(58) Tool E = 3e+007
Units: psi
Tool modulus of elasticity. Assume stainless steel 30E6.

(59) Tool Elongation = System Force/Tool K
Units: inch
The tool beam deflection is equal to the force applied to the beam divided by the spring constant of the beam.

(60) Tool K = Tool E*Tool Width*(Tool Cut Depth^3)/(4*(Tool Cut Length^3))
Units: inch*psi
The spring constant of the tool is equal to E*bt*ht^3/4L^3. See equation 4.1 in the chapter.

(61) Tool Position = Tool Elongation+Tool Pre Flatness-Linkage Loss
Units: inch
The tool position is simply the tool elongation (which is system force/tool beam spring constant) plus the tool pre flatness (machined into the tool) minus linkage loss. Linkage loss is an open variable for "what if" type modeling. I.e. what if in cycle 150 the system losses 400 u" due to pin position movement.

(62) Tool Pre Flatness = -0.0004
Units: inch
Machined into the tool is a preflatness of -0.0004 or 400 u". Think of it as a bow in the beam of -400 u".

(63) Tool Width = 0.165
Units: inch
The width of the beam. Input by program user.

(64) VLDDL = 0
Units: inch
Voltage Loss before DDL - simulates a condition where voltage is lost between Row Bow and lap.

(65) VLRAMP = 0
Units: volts
Voltage Loss between DDL and Ramp. Simulates a scenario where the module blocks are slightly discharged either during DDL block removal or prior to ramp processing.

(66) VLRB = 0
Units: volts
Voltage Loss before Row Bow - simulates a condition where the module block loses voltage (and thus stroke) before row is started.

(67) Voltage = MAX(IF THEN ELSE(Time < 75,(Computer Voltage Ramping+one)-Voltage Loss Before Row Bow,IF THEN ELSE(Time<120,60,IF THEN ELSE(Time<250,Computer Voltage Ramping-DDL Voltage Cycles,Computer Voltage Ramping-DDL Voltage Cycles-Voltage Loss Before Ramp)))*Full Discharge,0)
Units: volts
Voltage is the main variable for modulating the actuator extension. The voltage is forced to different values at various cycles. The voltage and actuator extension simulate values used in the closed loop lapping process.

(68) Voltage Loss Before DDL = IF THEN ELSE(Time>90,VLDDL,0)
Units: volts
A simple equation to turn the voltage loss off before 90 cycles. After 90 cycles the value is set equal to VLDDL.

(69) Voltage Loss Before Ramp = IF THEN ELSE(Time>250,VLRAMP,0)
Units: volts
After 250 cycles the voltage loss before ramp is set to VLramp, before 250 cycles it is set to 0. This was not used in the chapter 4 modeling.

(70) Voltage Loss Before Row Bow = IF THEN ELSE(Time>47,VLRB,0)
Units: volts
After 47 cycles the loss is set equal to the input variable of VLRB. This was not used in chapter 4 modeling, but was included for future use by the company, as requested.

Attachment 2

The following stress/strain data was obtained from the electrostrictive actuator vendor. The graph displays the impact of high compressive stresses on actuator displacement when 150 volts is applied.

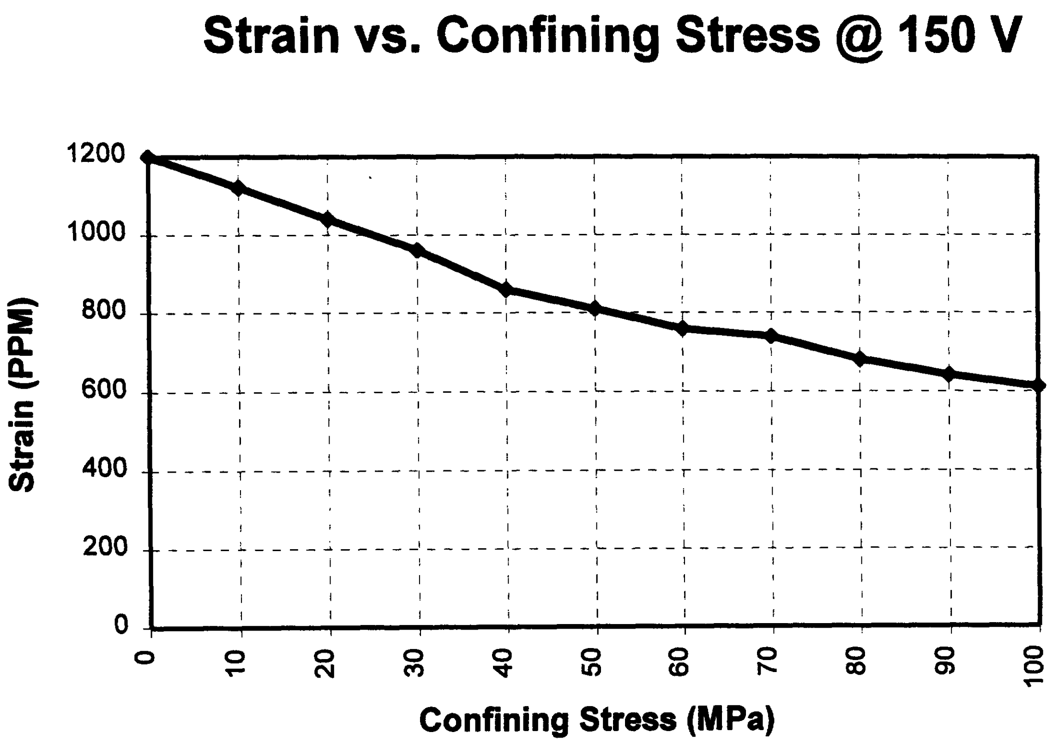

Figure 0-1

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