2.830J / 6.780J / ESD.63J Control of Manufacturing Processes (SMA 6303)
Spring 2008

Control of Manufacturing Processes

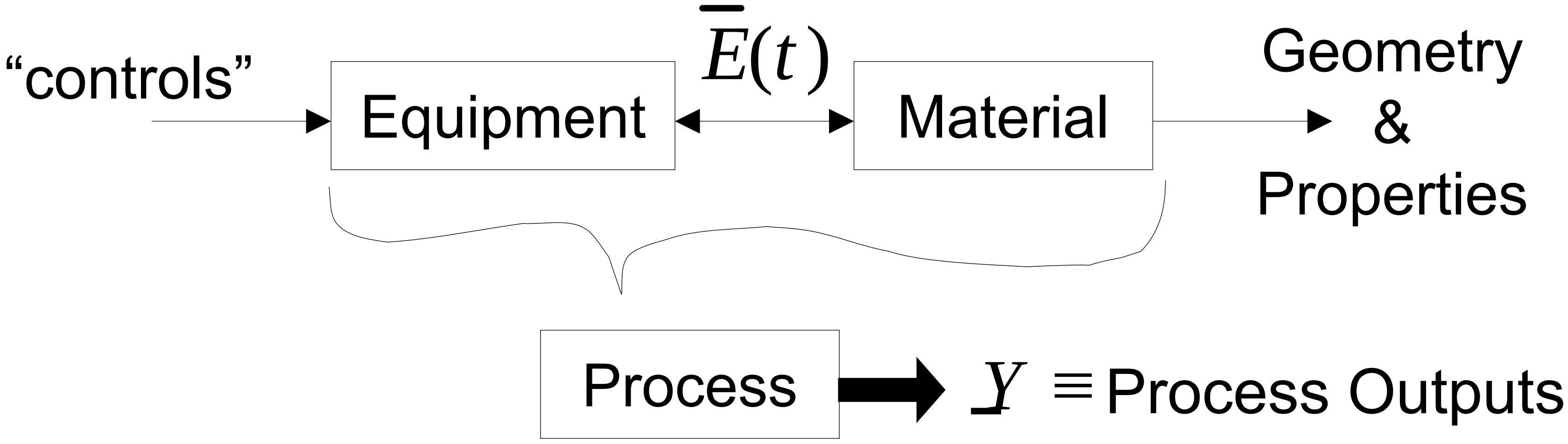
Subject 2.830/6.780
Spring 2008
Lecture #3
“Process Variation – Physical Causes and Interpreting Data”

February 12, 2008

Agenda

- Process Definitions
  - Geometry Change Causality
- Taxonomy for Control
  - Classification of Change Methods
- “Mechanical” Examples
  - Turning
  - Bending
  - Molding
- Origins of Variation
  - States and Properties

Process Model for Control



$\underline{Y} \equiv$ Process Outputs

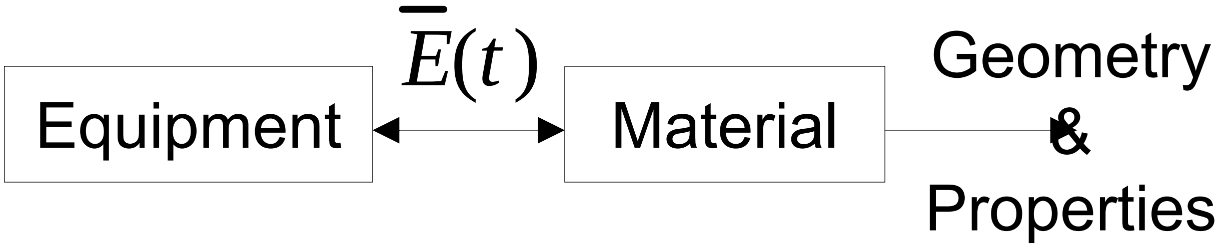
$$\underline{Y} = \Phi(\underline{\alpha})$$

$$\underline{\alpha} \equiv \text{process } \textit{parameters}$$

What are the α's?

Back to the Process: What Causes the Output Change?

- A Directed Energy Exchange with the Equipment



$$\bar{E}(t) \rightarrow \begin{Bmatrix} mechanical \\ electrical \\ thermal \\ chemical \end{Bmatrix}$$

Modes of Geometry Change?

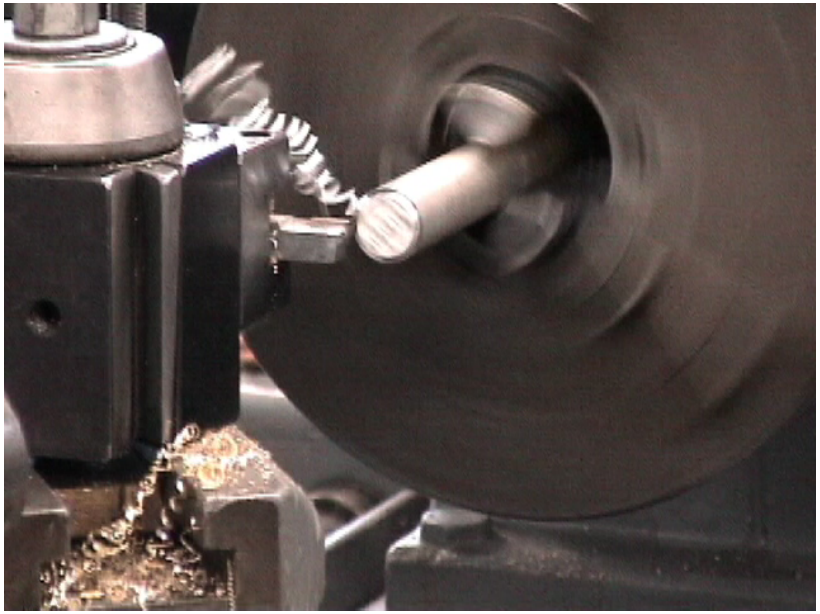
- **Removal** of Material
- Plastic **Deformation** of Material
- **Addition** of Material
- **Formation** of Material from a Gas or Liquid

- Any others???

What Controls the Geometry Change?

Location and Intensity of Energy Exchange

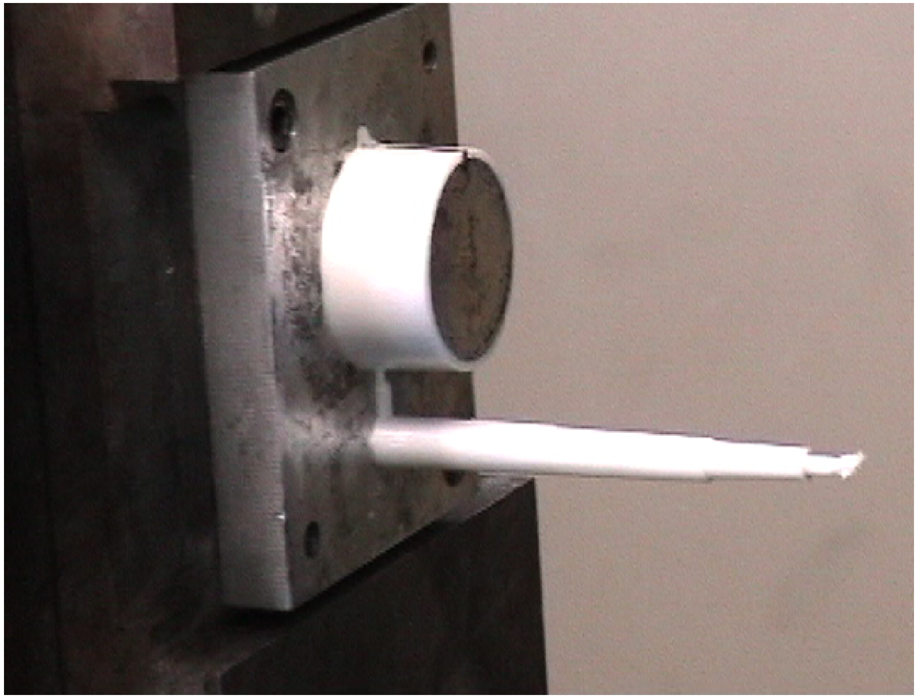
- Examples:
  - location of max. shear stress in turning



What Controls the Geometry Change?

Location and Intensity of Energy Exchange

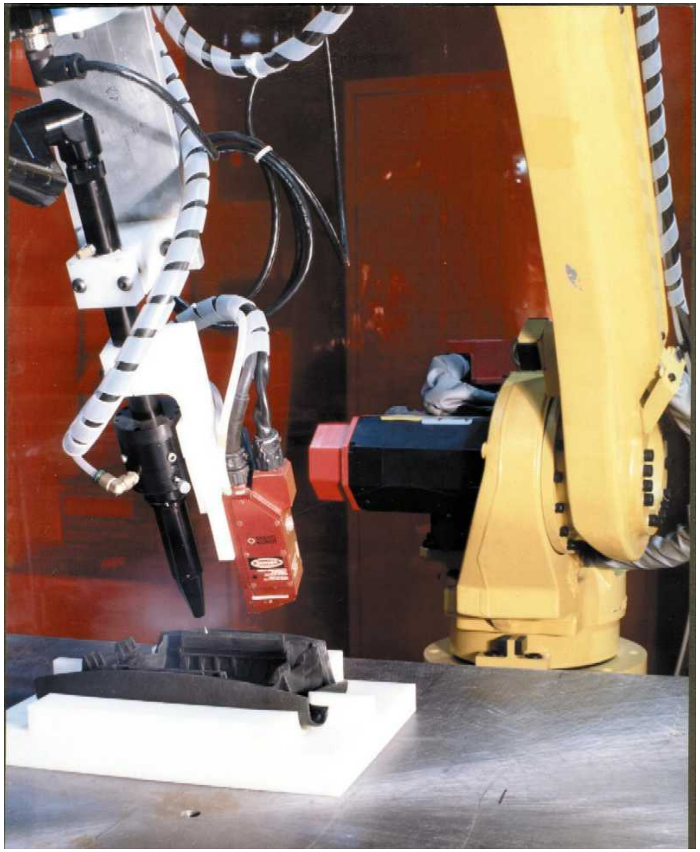
- Examples:
  - heat transfer at the mold surface in injection molding



Control of Geometry Change?

Location and Intensity of Energy Exchange

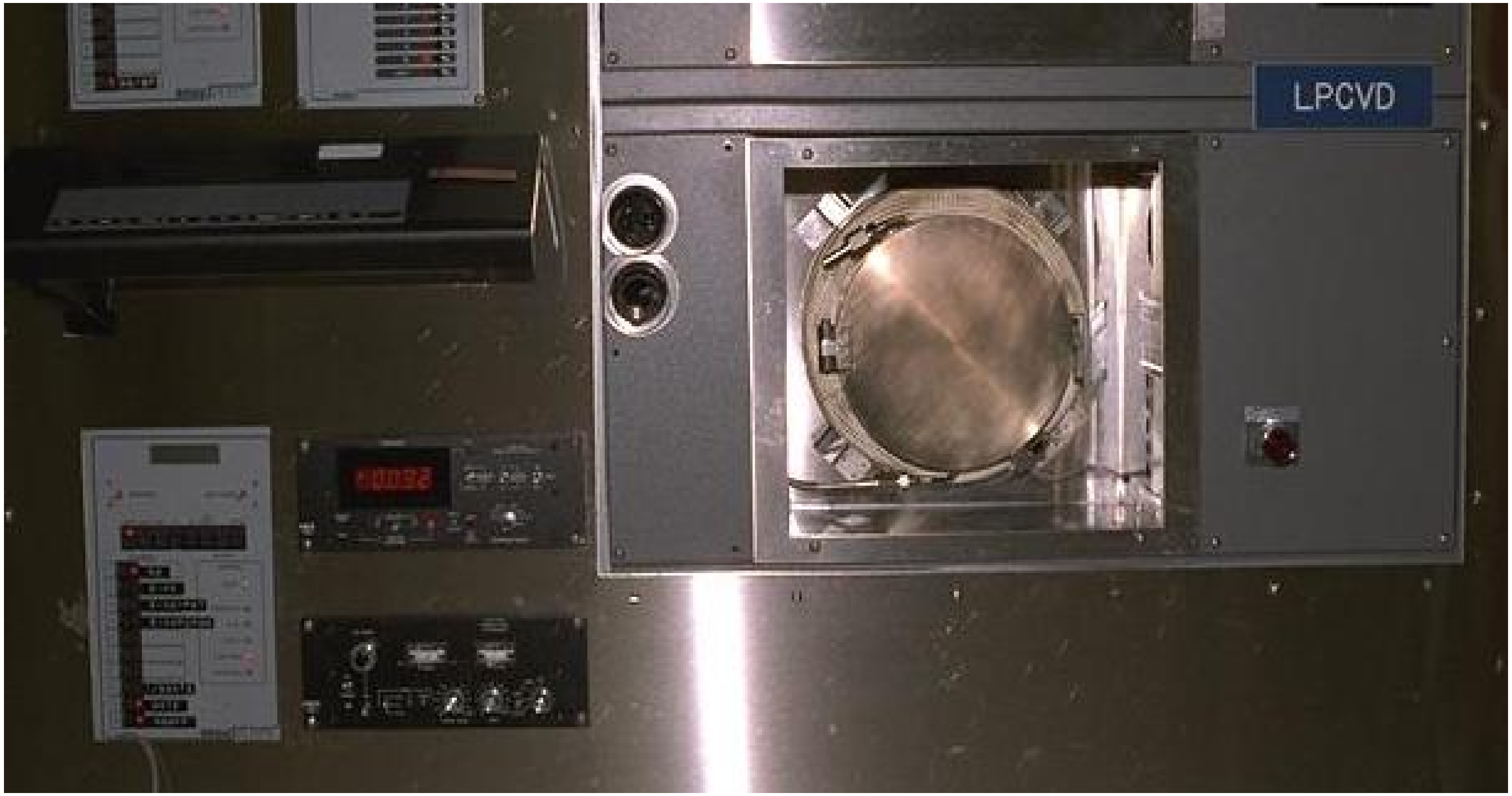
- Examples:
  - – location of laser beam in laser cutting



Control of Geometry Change?

Location and Intensity of Energy Exchange

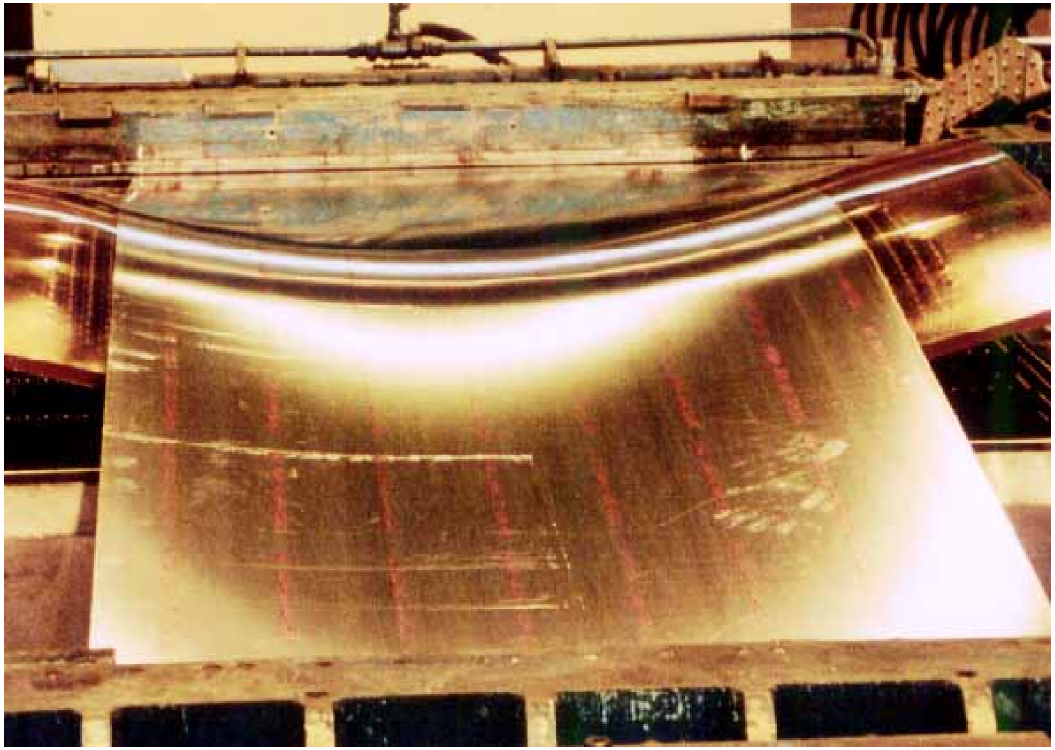
- reaction rate - time product on substrate surface in LPCVD



Control of Geometry Change?

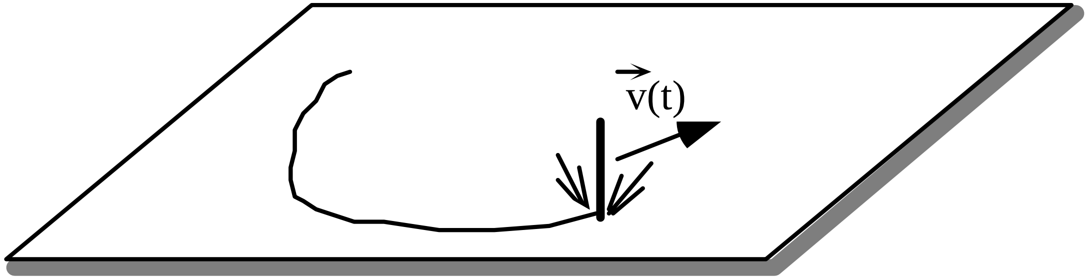
Location and Intensity of Energy Exchange

- displacement field in sheet forming :

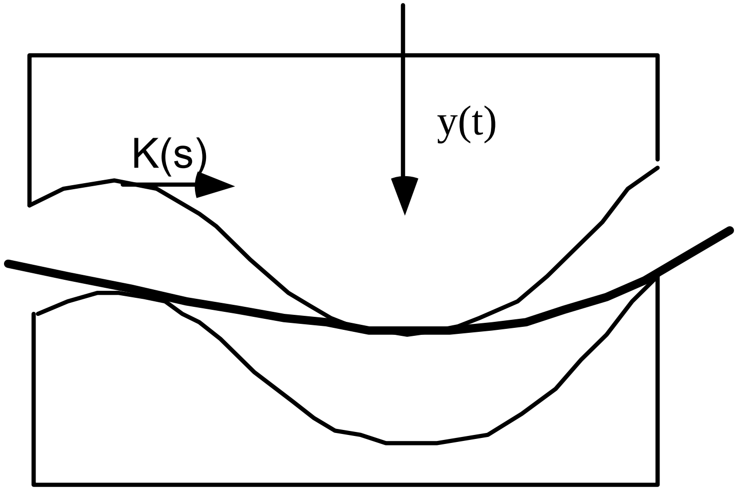


Two Extremes of Interactions

Area of E(t) << Total Area: Serial Process



Area of E(t) ~ Total Area: Parallel Process



Two Extremes of Interactions

- Concentrated, “Lumped” Energy Port
  - Small Area Wrt Total Part Geometry
- Distributed Energy Port
  - Area ~ Total Part Geometry

What Determines Part Geometry Change?

- For Lumped case:
  - time - trajectory of the port location
    - e.g. tool paths

- For Distributed Case:
  - Shape of the energy distribution
    - patterns
    - molds
    - masks

Examples

- Serial (Lumped) Processes
  - Machining - Tool Path
  - Laser Cutting - Beam path
  - Bending - Tool Depth
  - Stereolithography - Beam Path
  - Three D Printing - Binder Path

Examples

- Parallel (Distributed) Processes
  - Draw Forming - Die Shapes
  - Injection Molding - Mold Shape
  - Chemical Etching - Mask Shape
  - CMP - Tool Shape
  - Plating - Substrate Shape

Toward a Process Taxonomy

- Classify by Change Mode
  - Why?
- Classify by Intera arallel)

Sensitivity, resolution

  - So what?
- Classify by Energy Domain
  - Who cares??

Flexibility, controllability, rate

Rate, resolution

Process Taxonomy for Control

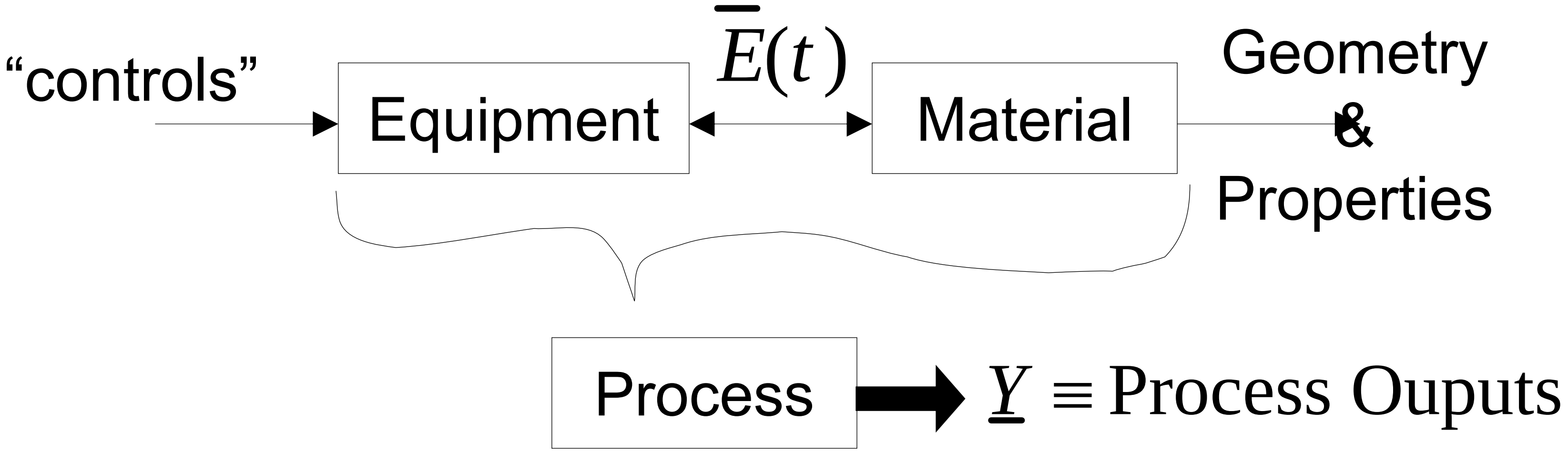
Transformation Mode	**REMOVAL**							
	SERIAL				**PARALLEL**			
Energy Source	Mechanical	Thermal	Chemical	Electrical	Mechanical	Thermal	Chemical	Electrical
	Cutting	*Laser Cutting*		*WIRE EDM*	*Die Stamping*		*ECM*	*EDM*
	Grinding	*"Flame" Cutting*			*CMP*		*Photolithography*	
	Broaching	*Plasma Cutting*					*Chem Milling*	
	Polishing							
	Water Jet							

Transformation Mode	**ADDITION/JOINING**							
	SERIAL				**PARALLEL**			
Energy Source	Mechanical	Thermal	Chemical	Electrical	Mechanical	Thermal	Chemical	Electrical
	Ultrasonic	*Laser*		*E-Beam Welding*	*HIP*	*Sintering*	*LPCVD*	
	Welding	*Sintering*		*Arc Welding*	*Inertia Bonding*		*Plating*	
	3D Printing			*Resist. Welding*	*Phys. Depos.*			

Transformation Mode	**FORMATION**							
	SERIAL				**PARALLEL**			
Energy Source	Mechanical	Thermal	Chemical	Electrical	Mechanical	Thermal	Chemical	Electrical
		Plasma Spray	*Stereolithography*			*Casting*	*Diffusion*	
		DBM				*Molding*	*Bonding*	

Transformation Mode	**DEFORMATION**							
	SERIAL				**PARALLEL**			
Energy Source	Mechanical	Thermal	Chemical	Electrical	Mechanical	Thermal	Chemical	Electrical
	Bending	*Line Heating*			*Drawing*			
	Forging(open)				*Forging(die)*			
	Rolling							

Process Model for Control



“controls”

Equipment

$\overline{E}(t)$

Material

Geometry & Properties

Process

$\underline{Y} \equiv \text{Process Ouputs}$

$$\underline{Y} = \Phi(\underline{\alpha})$$

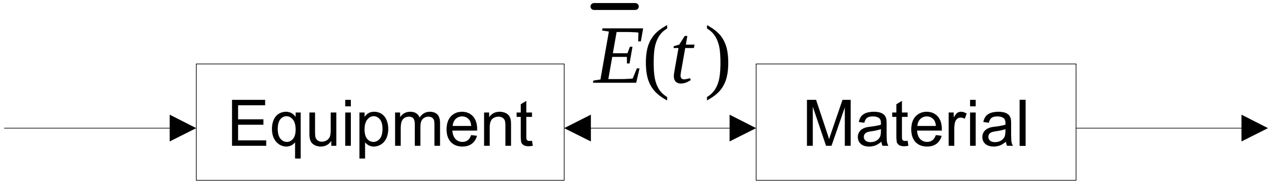
$$\underline{\alpha} \equiv \text{process } \textit{parameters}$$

What are the α’s?

Process Parameters

- Equipment Energy “States”
- Equipment Constitutive “Properties”

- Material Energy “States”
- Material Constitutive ”Properties”



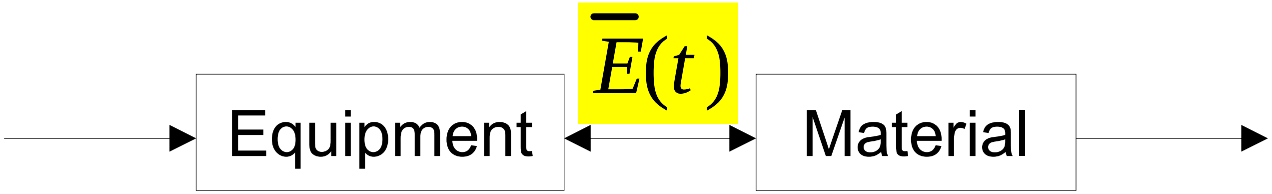
$\overline{E}(t)$

Equipment

Material

Energy States

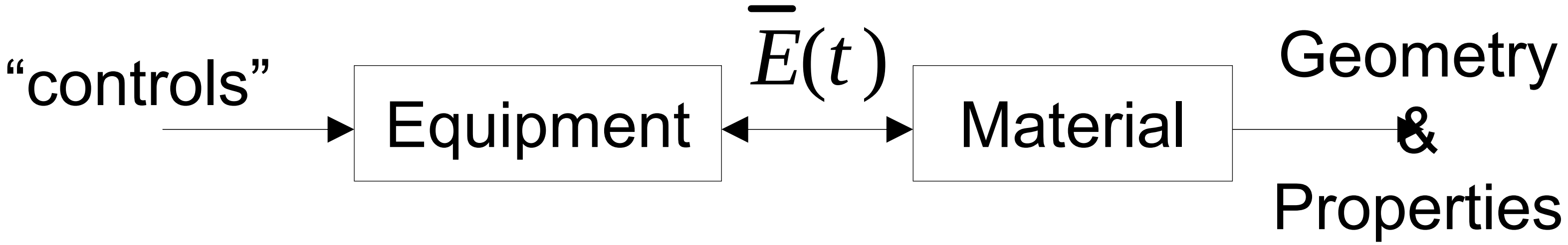
Energy Domain	Energy or Power Variables
Mechanical	F, v ; P, Q or F, d ; σ, ε
Electrical	V, I
Thermal	$T, ds/dt$ (or dq/dt)
Chemical	chemical potential, rate



Properties

- *Extensive*: GEOMETRY
- *Intensive*: Constitutive Properties
  - Modulus of Elasticity, damping, mass
  - Plastic Flow Properties
  - Viscosity
  - Resistance, Inductance, Capacitance
  - Chemical Reactivity
  - Heat Transfer Coefficient

A Model for Process Variations



"controls"

Equipment

$\overline{E}(t)$

Material

Geometry & Properties

- Recall: $\underline{Y} = \Phi(\underline{\alpha})$

- One or more α's "qualify" as inputs : $\underline{u}$

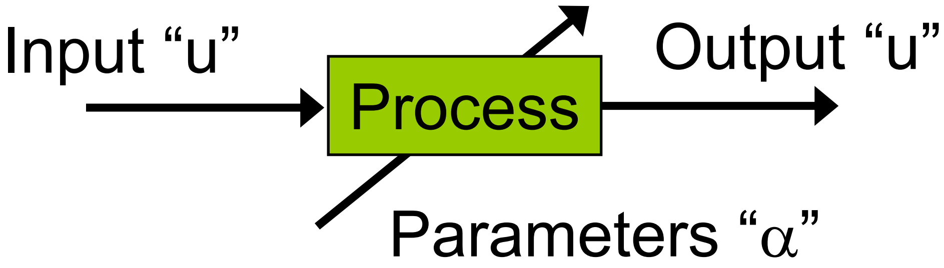
$$\underline{Y} = \Phi(\underline{\alpha}, \underline{u}); \qquad \underline{u} = \text{vector of inputs}$$

- The first order Variation ΔY gives the "Variation Equation"

Parallels From Lecture 2

Image removed due to copyright restrictions. Please see Fig. 26 in Boning, D. S., et al. "A General Semiconductor Process Modeling Framework." *IEEE Transactions on Semiconductor Manufacturing* 5 (November 1992): 266-280.

The Variation Equation



$$\Delta Y = \frac{\partial Y}{\partial \alpha} \Delta \alpha + \frac{\partial Y}{\partial u} \Delta u$$

Disturbance Sensitivity

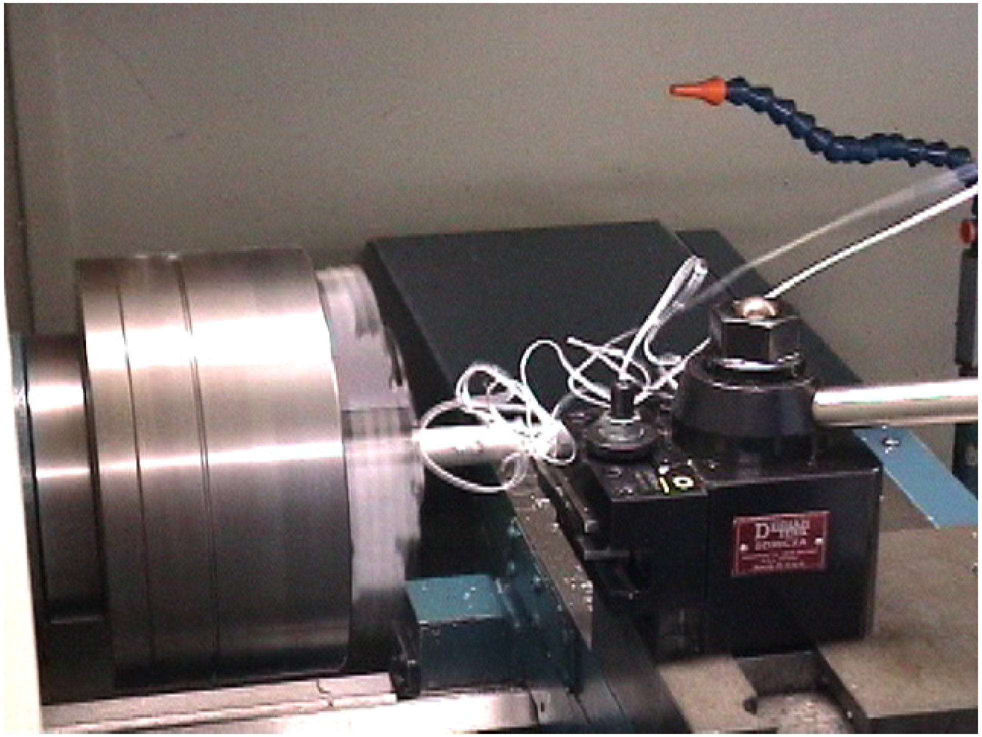
Disturbances

Control Sensitivity or “Gain”

Control Inputs

Simple Machining

- Process Type?
- Equipment States and Properties?
- Material States and Properties?

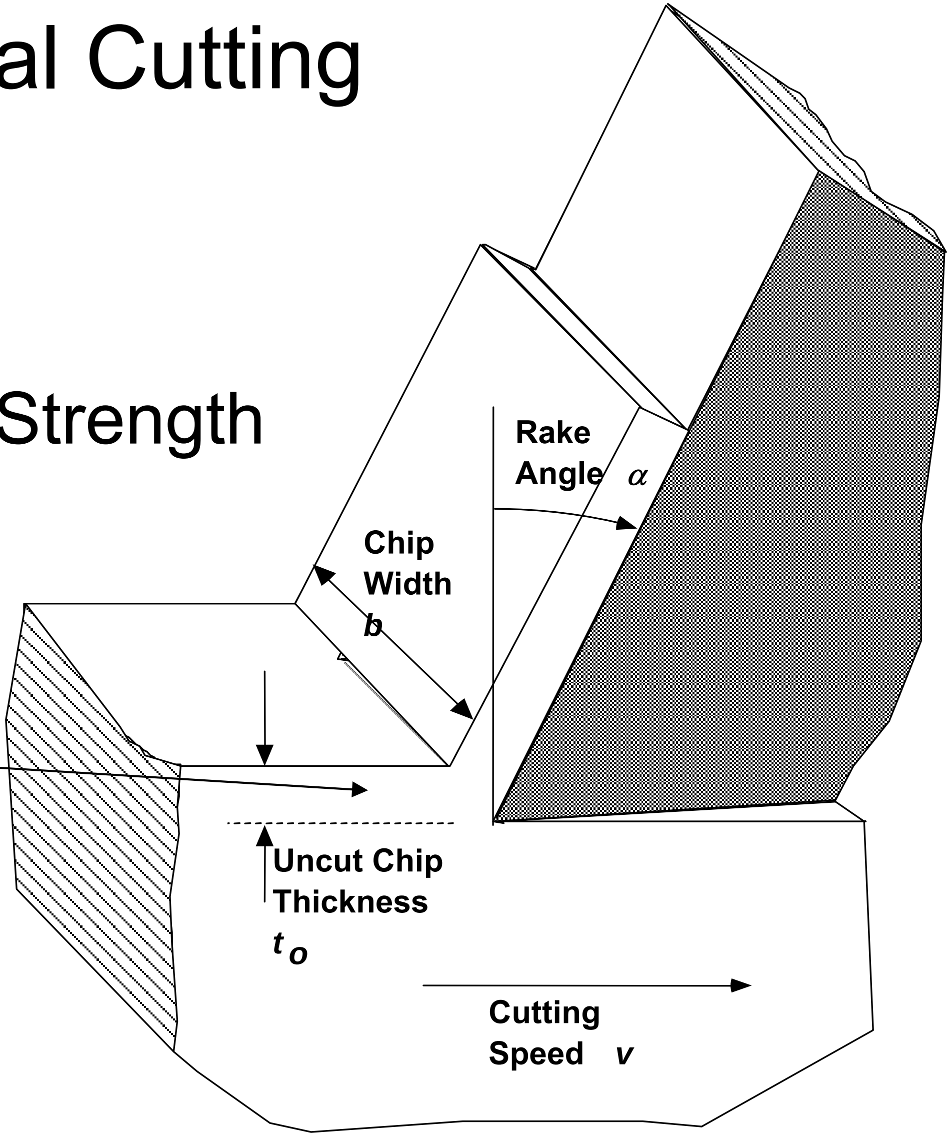


Cutting Force Model
Orthogonal Cutting

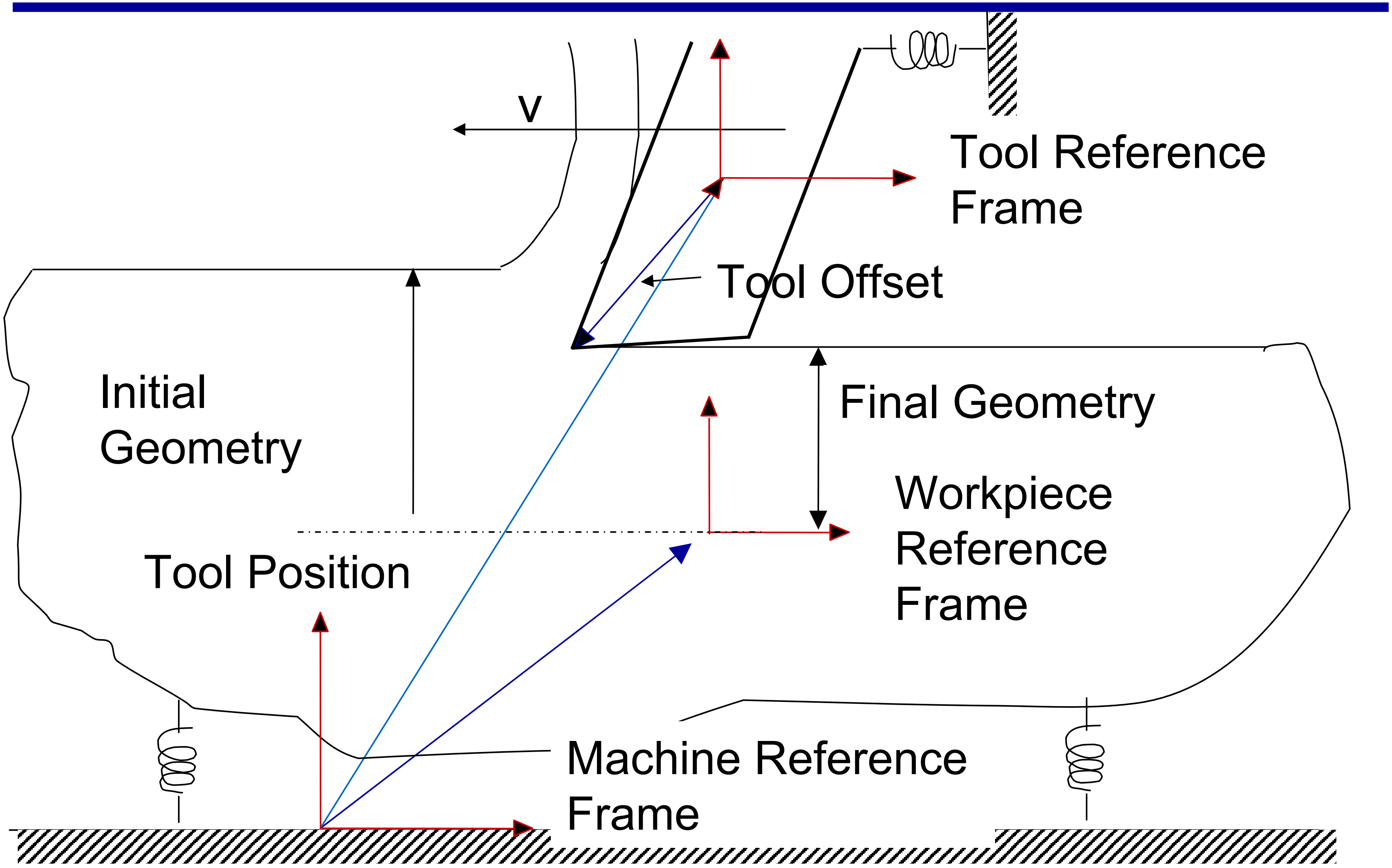
F_c="Strength" x Area

Strength = Ultimate Tensile Strength (UTS)

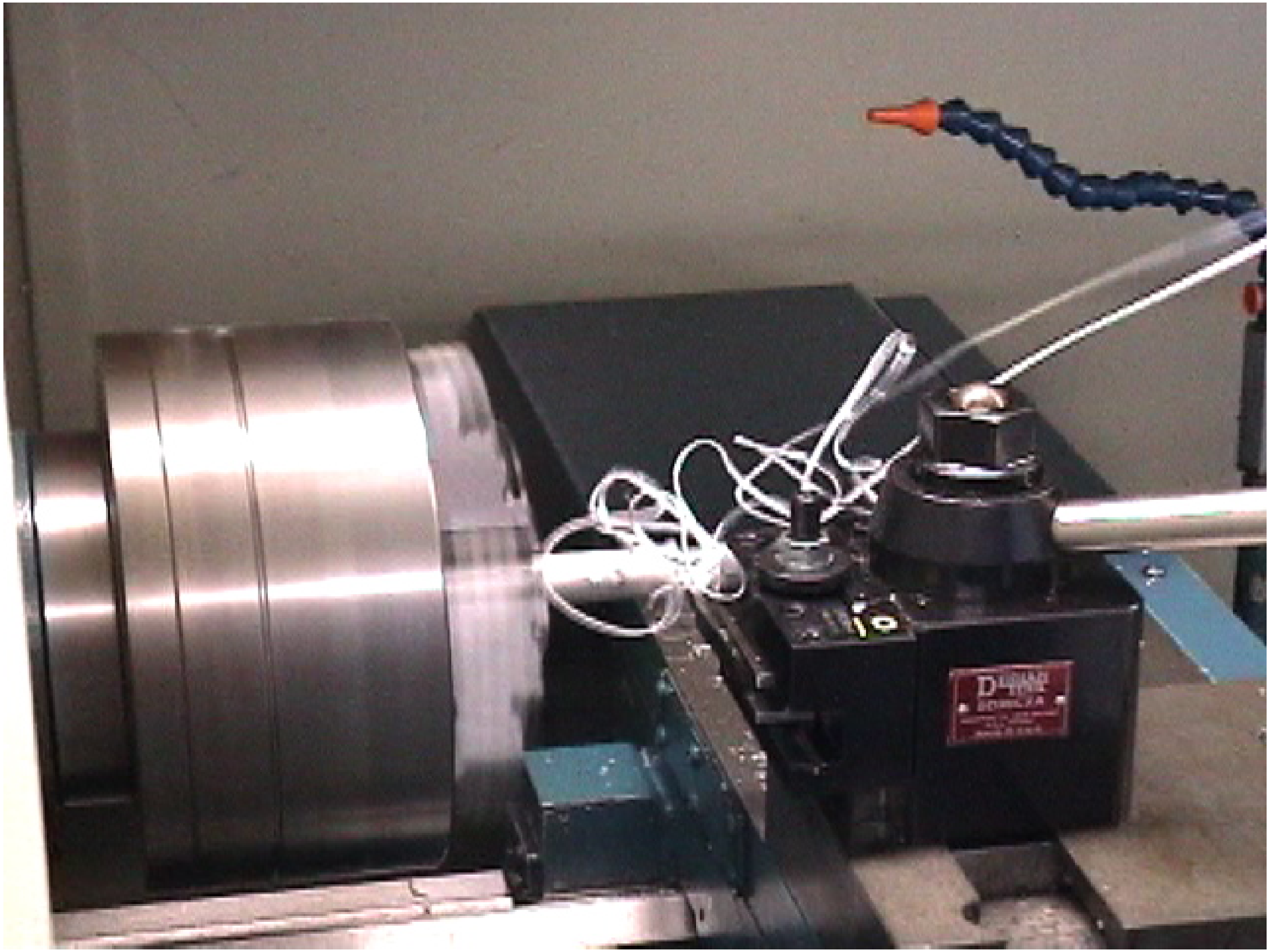
Area ~ b t_o

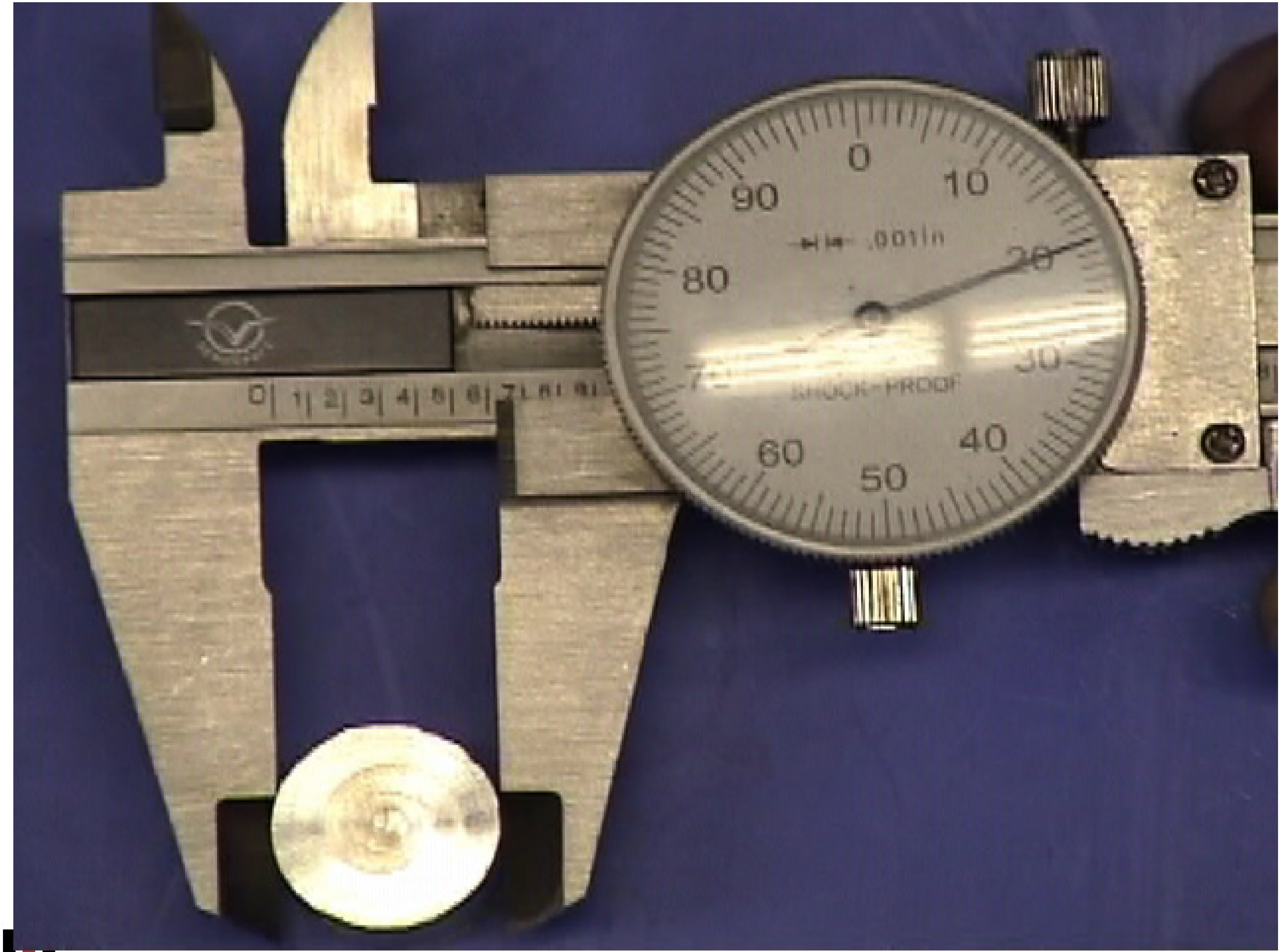


Sources of Variation?

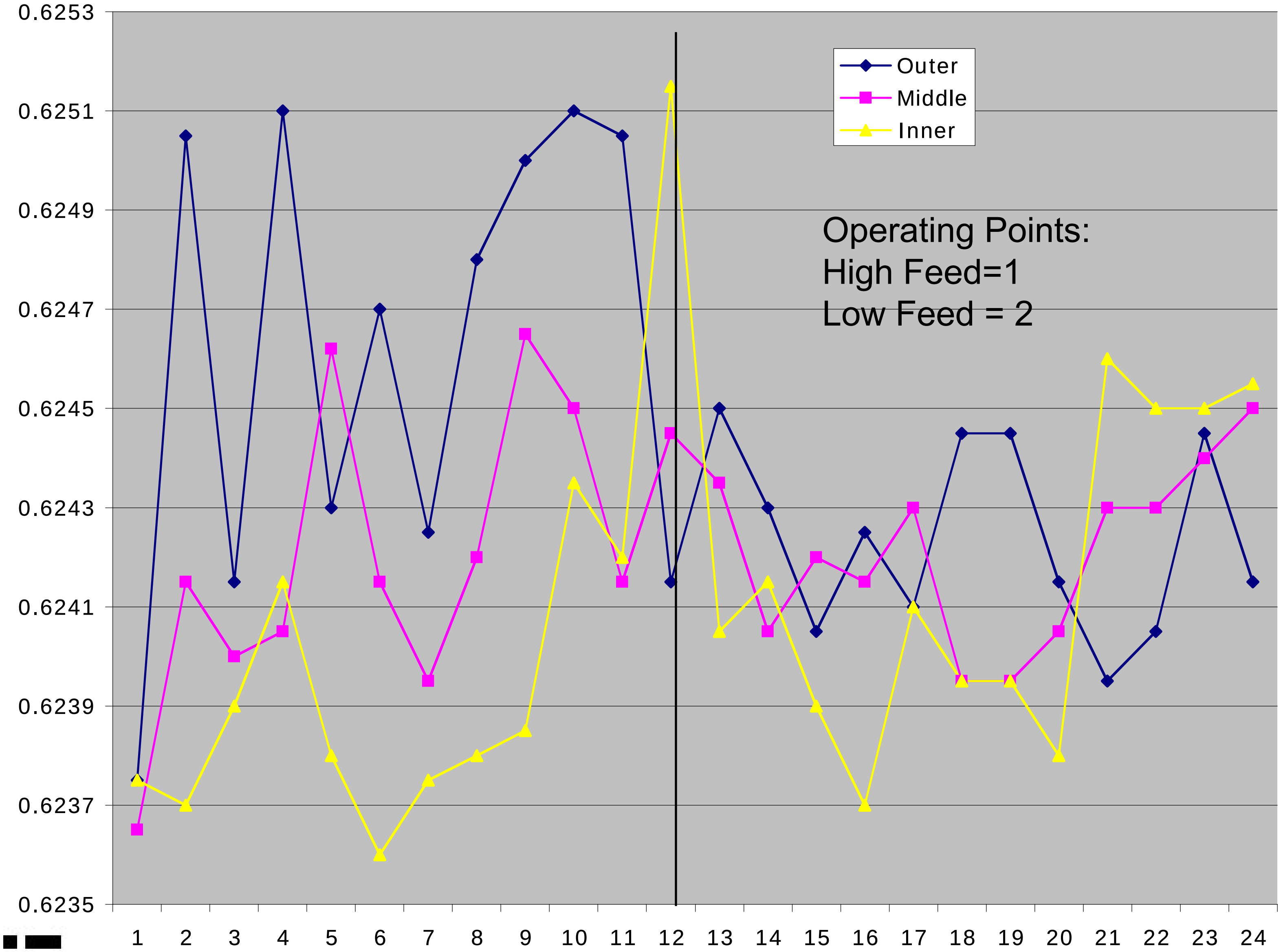


Simple Machining (Orthogonal Turning



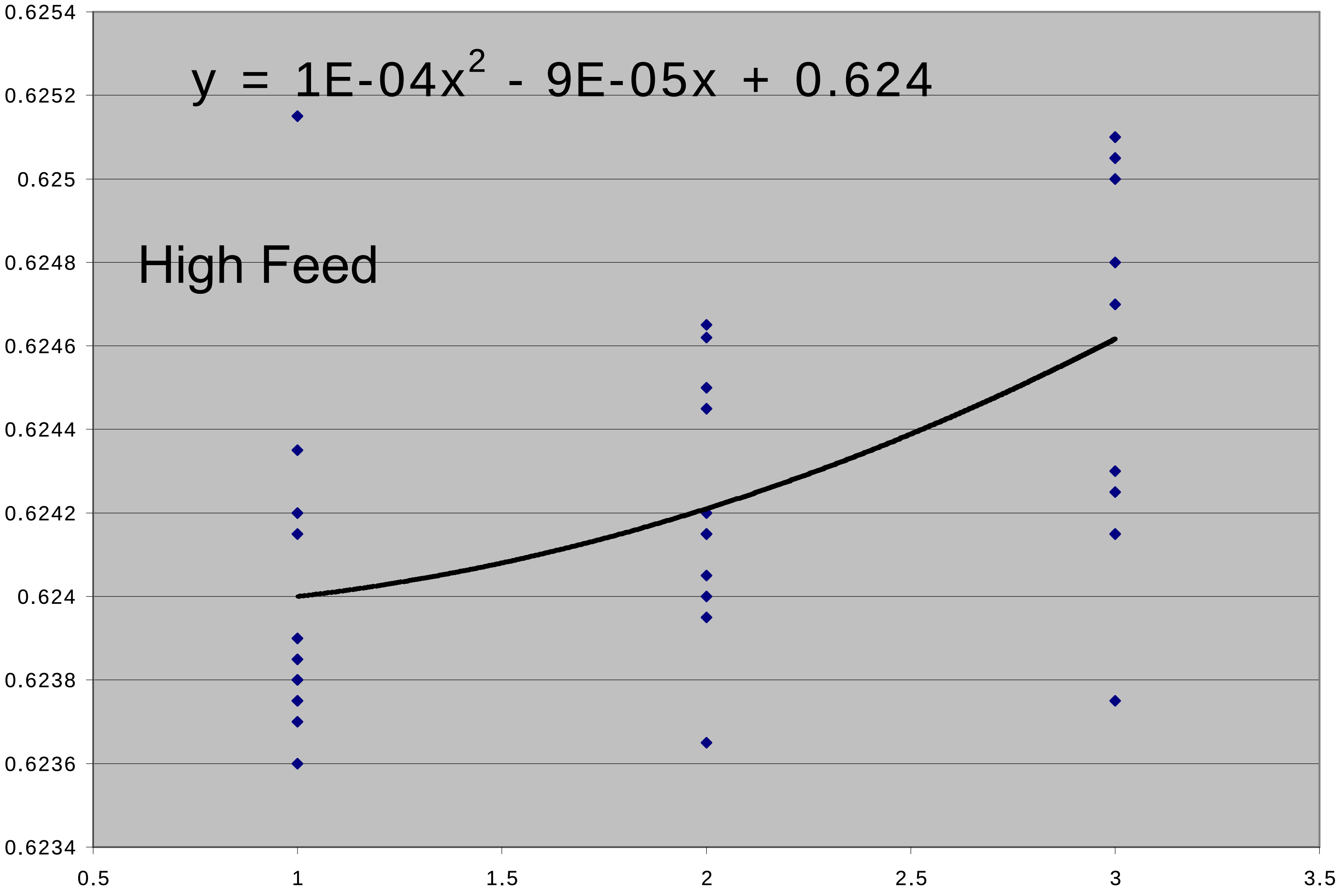

0
10
20
30
40
50
60
70
80
90
.001in
SHOCK-PROOF
0 1 2 3 4 5 6 7 8 9

CNC Data

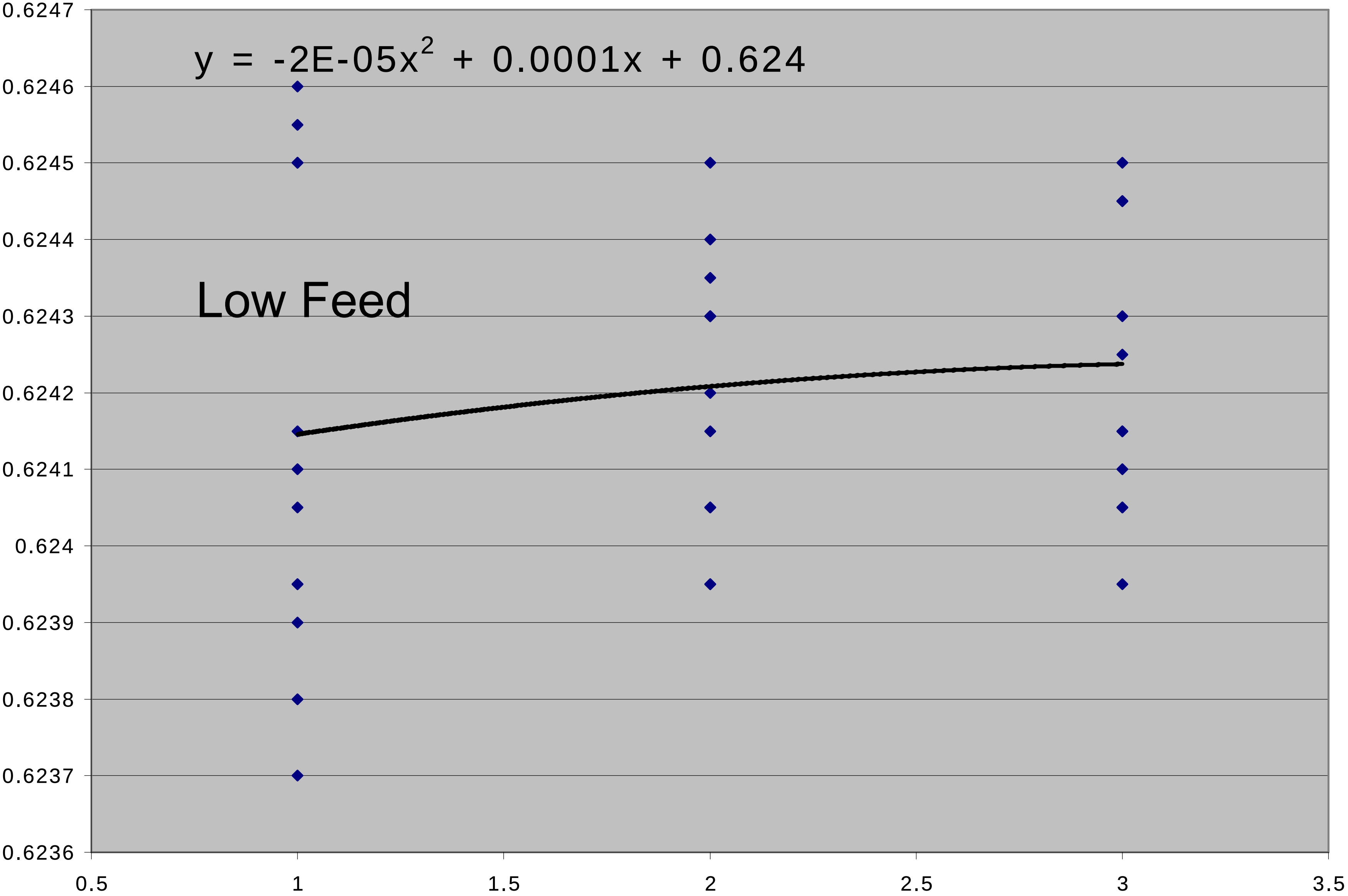


Operating Points:
High Feed=1
Low Feed = 2

Average Values



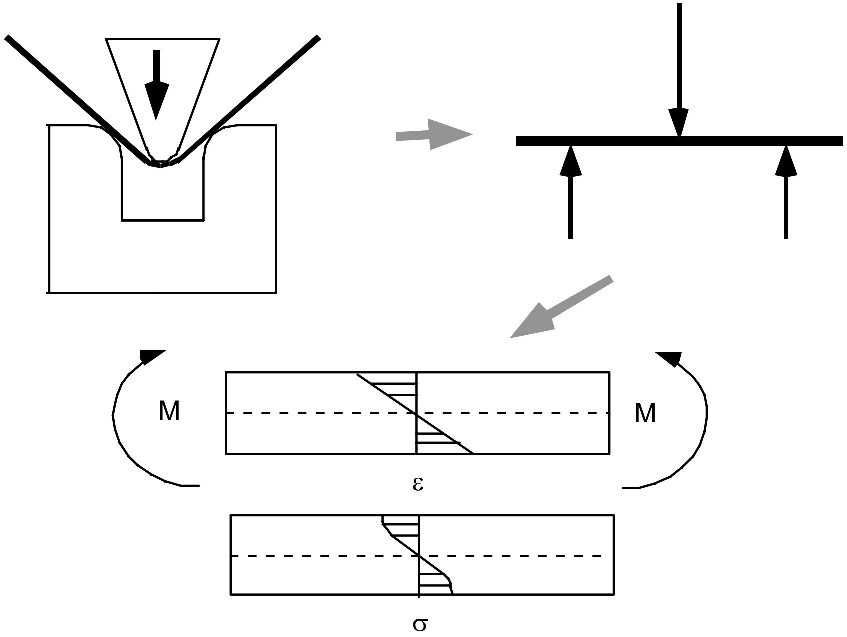
Average Values



Machining: Conclusions

- Geometry Transformation is (In General) well behaved
  - Not highly sensitive to material property variations
  - New Surface Where Tool is Located
- Dominant Sources of Variation:
  - Tool Positioning errors - Equipment Properties and States
- Feedback control of Positions is a good idea -> CNC control!

Brake Bending



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http://www.falconfab.com/MVC-016F.JPG

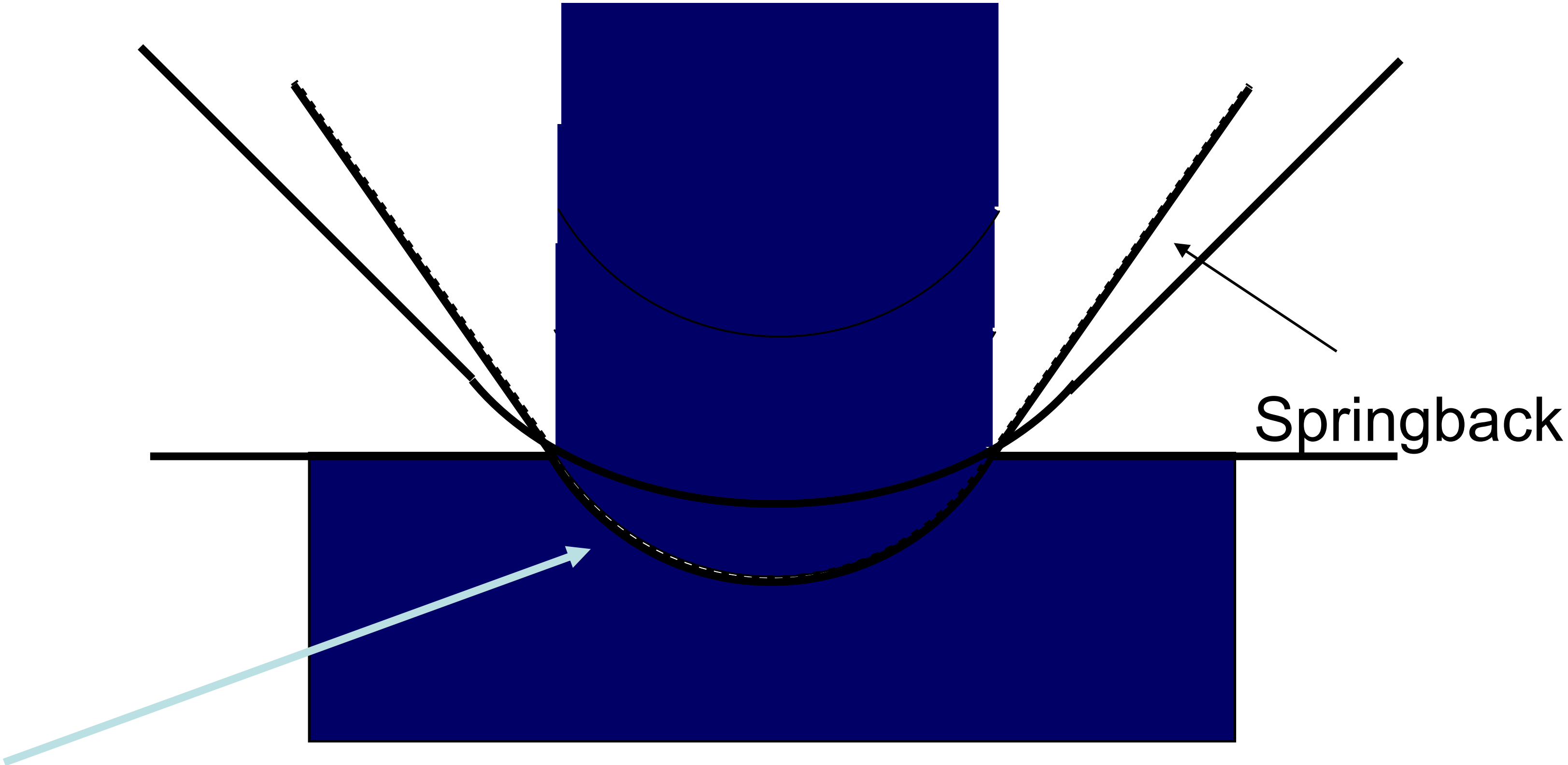
http://www.falconfab.com/MVC-007F.JPG

http://edevice.fujitsu.com/fj/DATASHEET/epk/fpt-100p-m20.pdf

Bending

- Process Type?
- Equipment States and Properties?
- Material States and Properties?

Simple Model : Pure Moment Bending

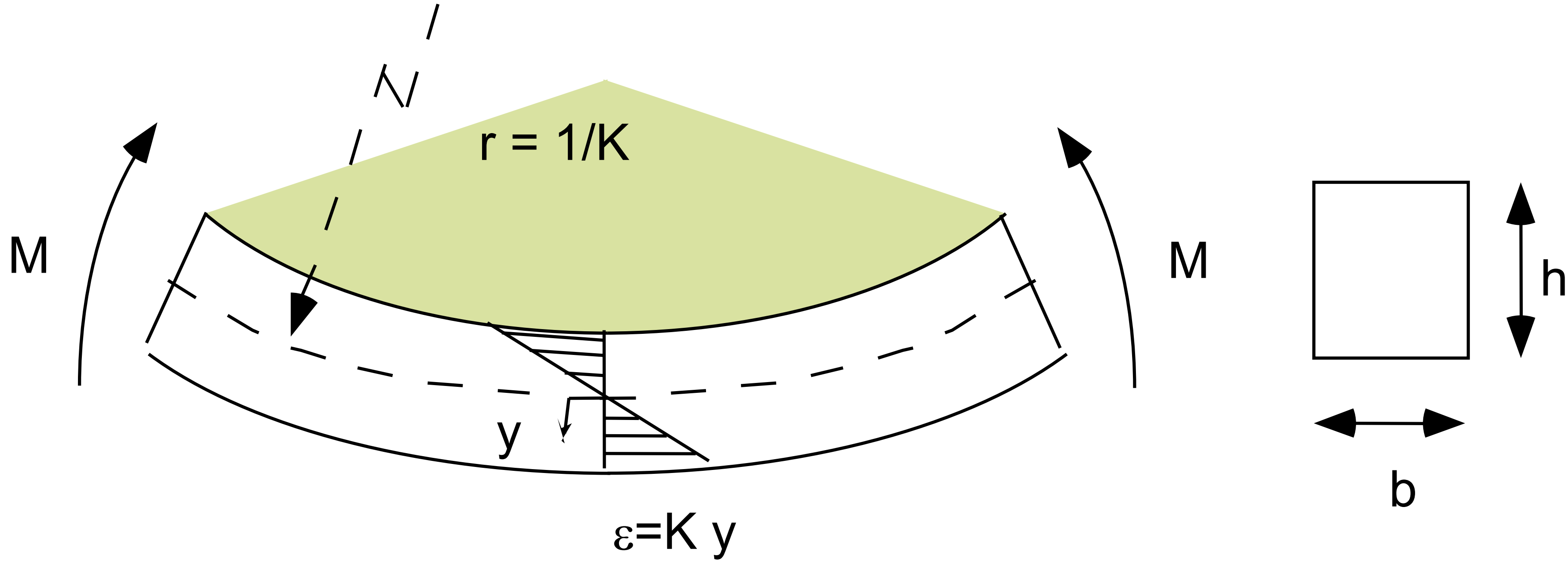


Constant Radius Tool

Simple Bending Mechanics: Parameter Effects

- Tool Shape (R_{tool}) determines the shape under load
- Elastic Springback determines the final shape
- What determines the springback?

Simple Bending Model



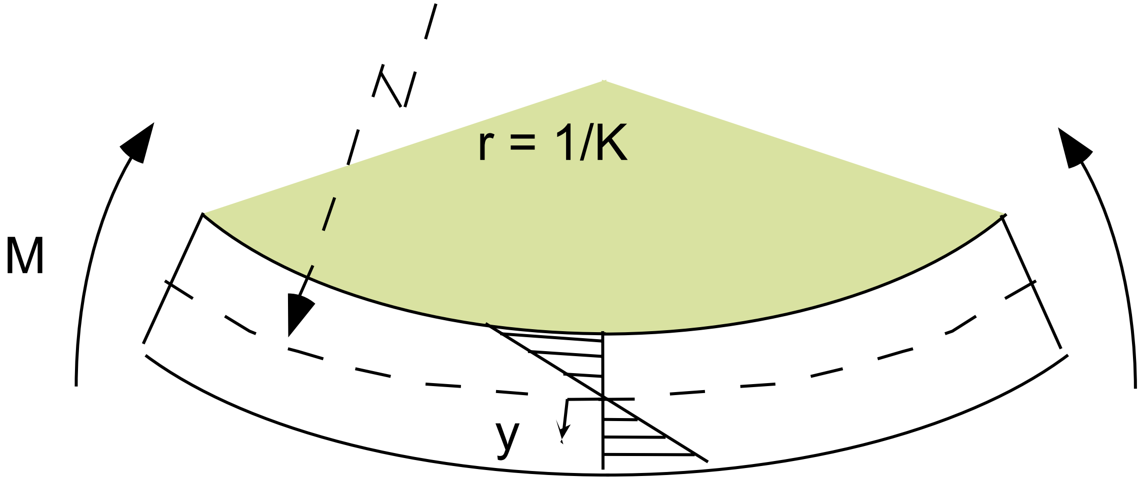
K = curvature of the tooling

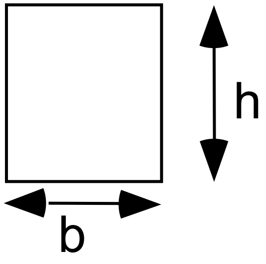
h = thickness of the sheet

$\varepsilon(y)$ = through thickness strain

What is M(K)
(or K(M)) ?

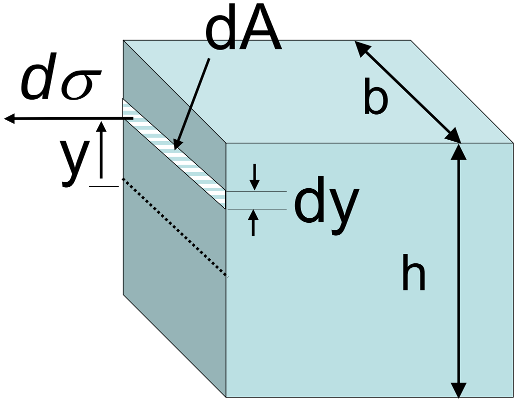
Simple Beam Theory





$$\varepsilon(y) = Ky$$

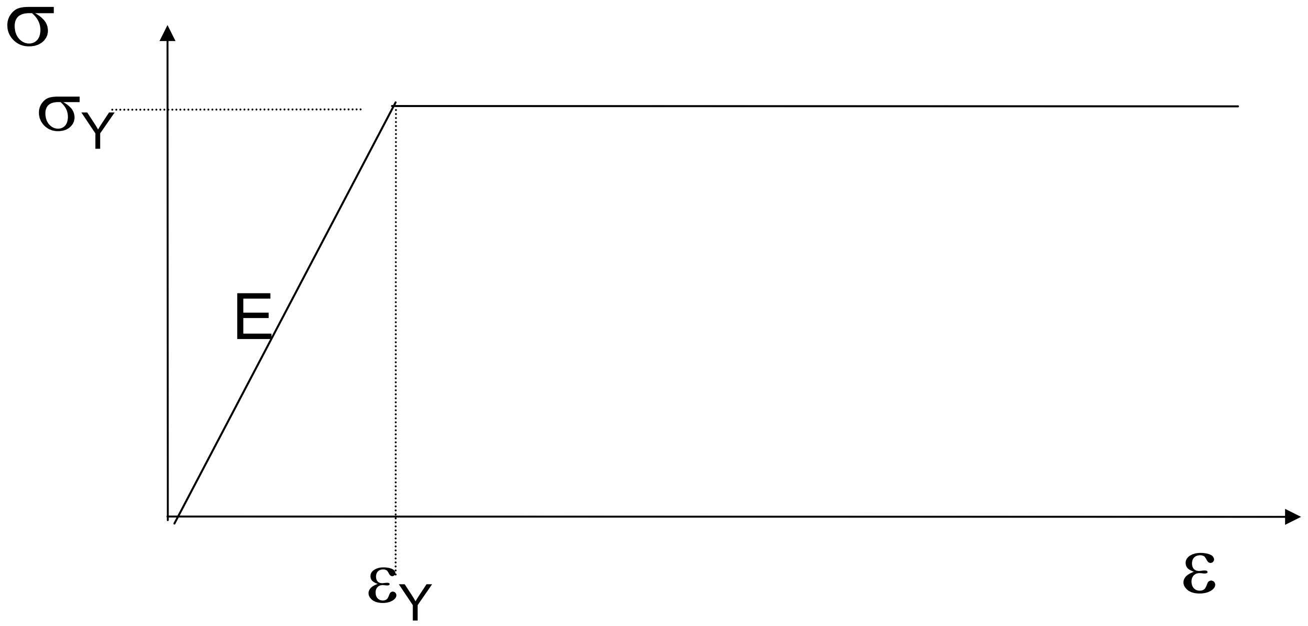
ε=K y



$$M = \int_{-h/2}^{h/2} \sigma(y)\underbrace{y}_{\text{moment arm}}\underbrace{bdy}_{\text{dA}}$$

$$\sigma(y) = ?$$

Elastic Perfectly Plastic Model

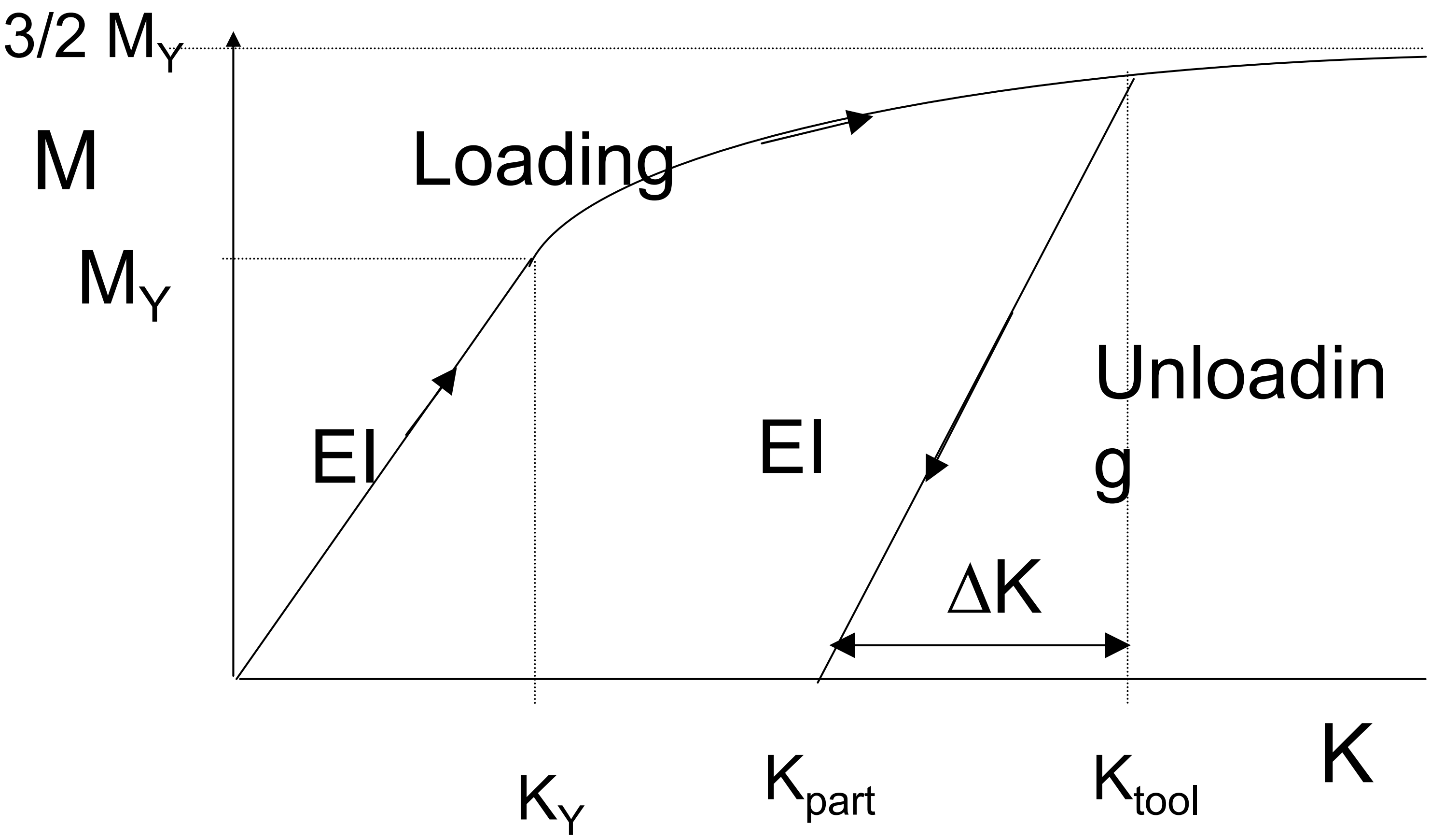


$$K_Y = \varepsilon_Y / (h / 2)$$

$$M = \frac{3}{2} M_y \left(1 - \tfrac{1}{3} \left(\frac{K_y}{K} \right)^2 \right)$$

$$M_Y = EI \;\; K_Y$$

The M-K Curve



Final Shape: Springback

$$\Delta K = \frac{M_{\max}}{EI} \therefore K_{part} = K_{tool} - \Delta K$$

K = shape of tool

E= material property

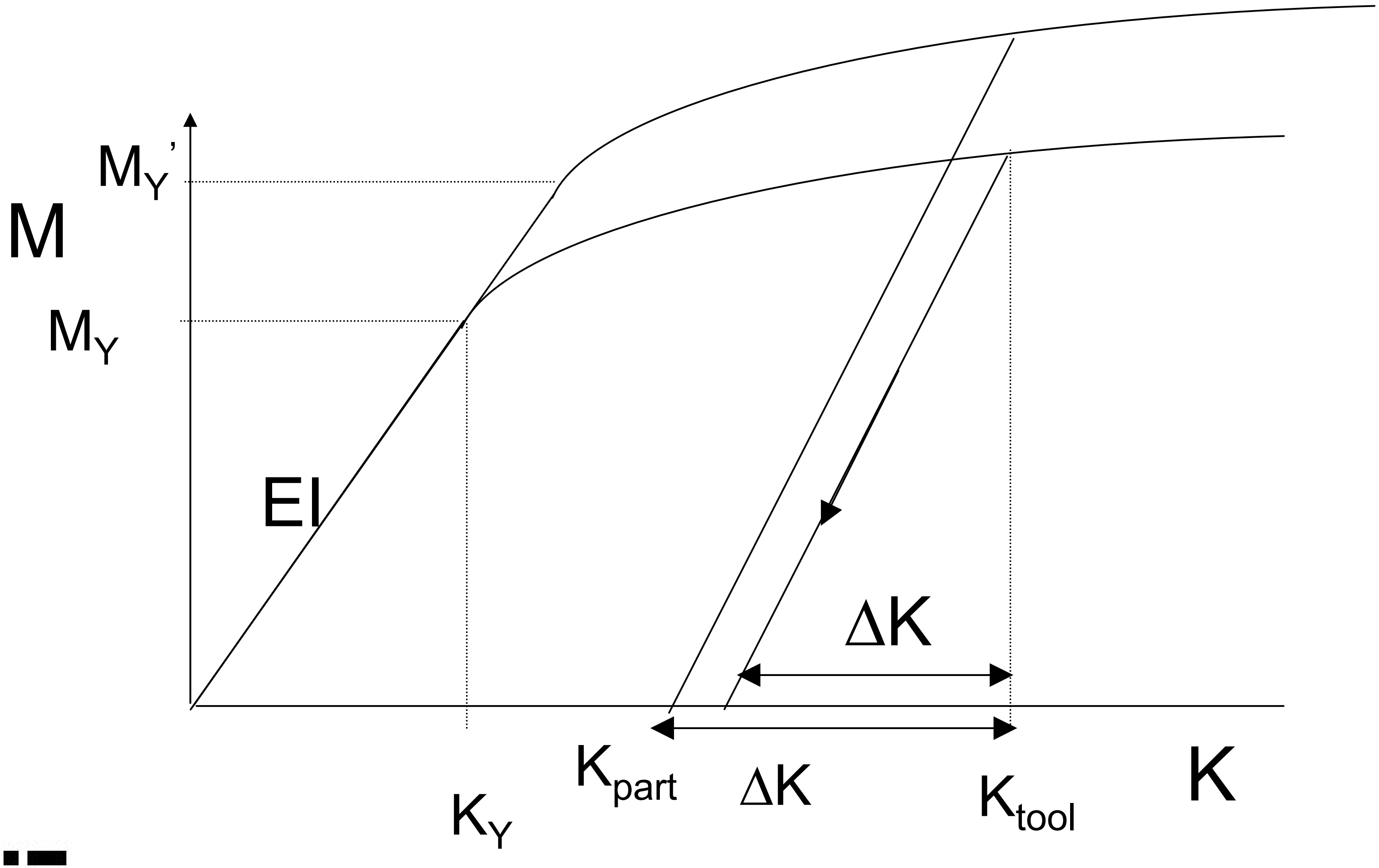
$$I = \frac{1}{12} bh^3 \quad cubic \text{ dependence on thickness}$$

$$M_{\max} = ?$$

$$M_{\max} = \Phi\,(\mathrm{K_Y}, EI)$$

Strong Dependence on yield properties

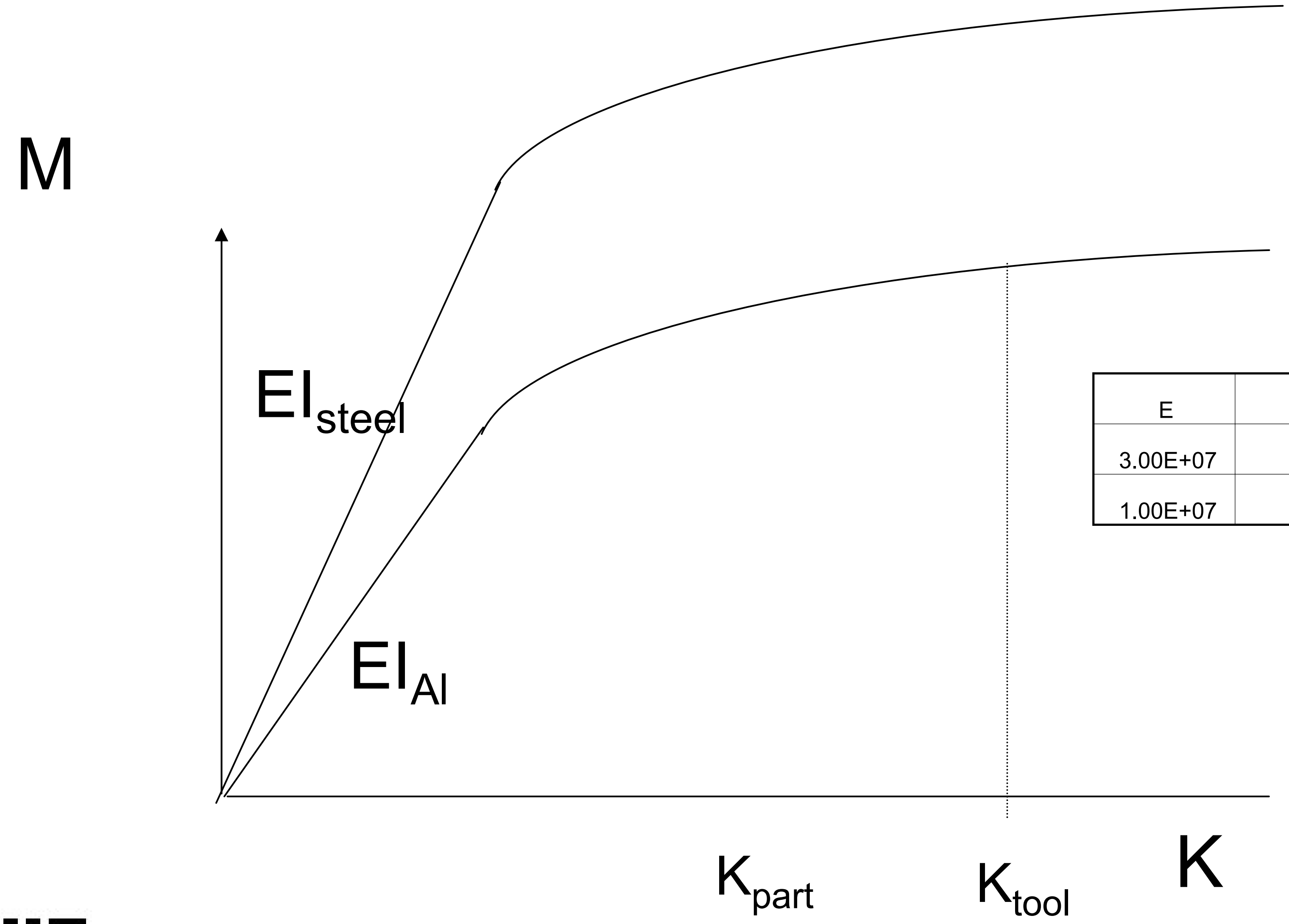
Effect of Material Variations: Increase in Yield Stress



Bending Experiments

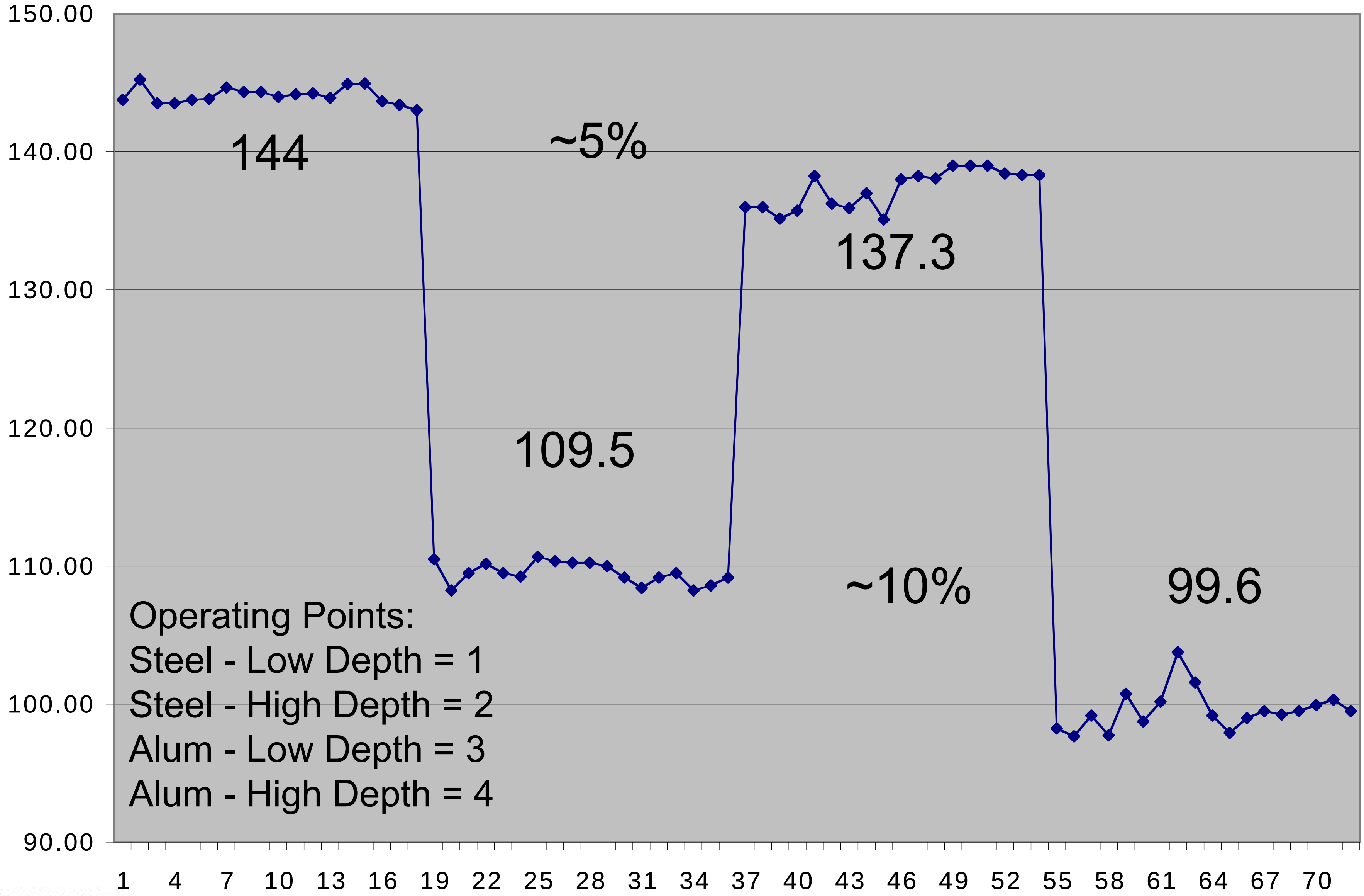
- Bend to 2 different depths
- Two different materials
  - – 0.028” Steel
  - – 0.032” Aluminum

Steel vs. Aluminum



E	t	EI
3.00E+07	0.028	54.88
1.00E+07	0.036	38.88

Bending by Operating Point



Operating Points:
Steel - Low Depth = 1
Steel - High Depth = 2
Alum - Low Depth = 3
Alum - High Depth = 4

Other Possible Variations

- Yield Stress (+ 10%reported)
  - Chemistry, working history
- Thickness
  - Rolling mill quality
  - Design vs. manufacturing specs
- Tooling Errors

Conclusions

- Some Variations Easily Explained
  - Deterministic parameter changes
    - Thickness and Material Selection Δm_p (Material Parameter)
  - Intentional Input changes
    - Depth changes Δe_s (Equipment state)
- Other Variations ???
  - Property Variations within Material Δm_p
  - Machine Errors Δe_p and Δe_s (e.g. deflection and position error)

$$\Delta Y = \frac{\partial Y}{\partial \alpha} \Delta \alpha + \frac{\partial Y}{\partial u} \Delta u$$

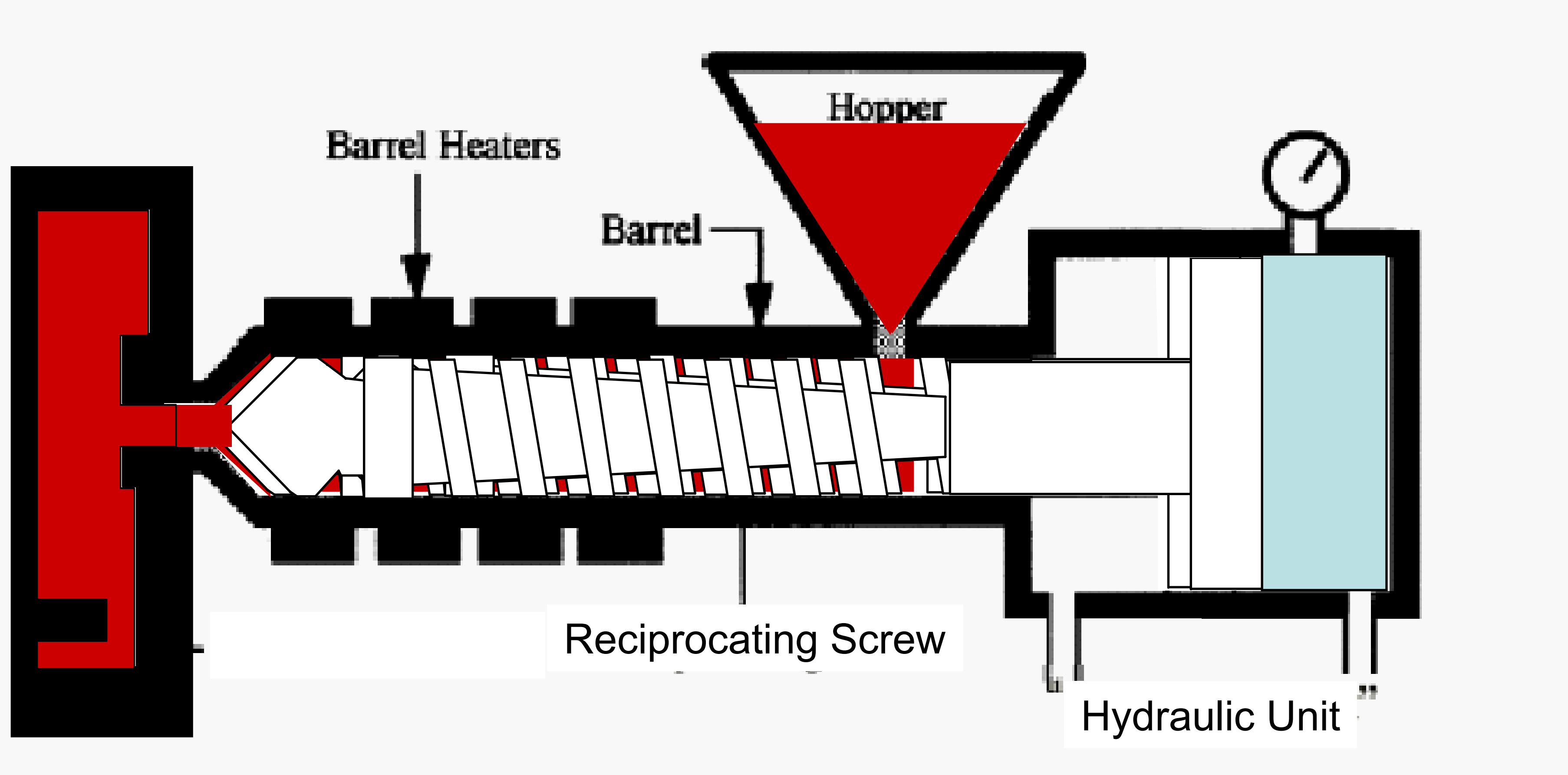
Conclusions for Brake Bending

- Equipment Errors have Strong Effect on Final Shape
  - Punch Penetration -> Δe_s (Equipment state)
  - Die Width -> Δe_p (Equipment Parameter)

SO WHAT? → **Large $\partial Y/\partial \alpha$**

Large $\Delta\alpha$

Injection Molding

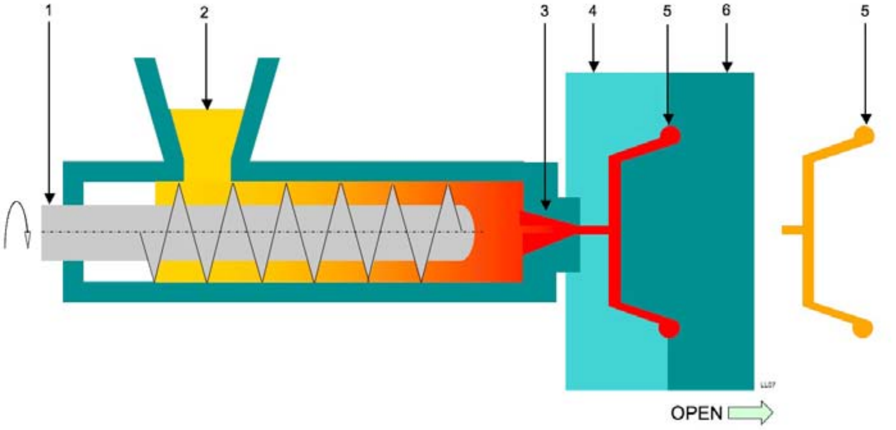


Injection Molding Process

Process Type?

Equipment States and Properties?

Material States and Properties?



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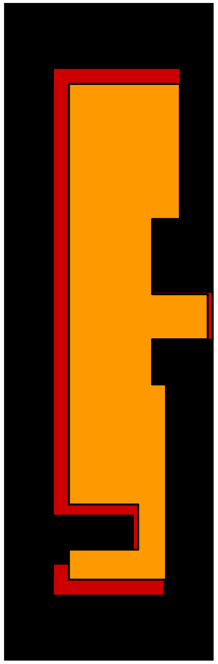
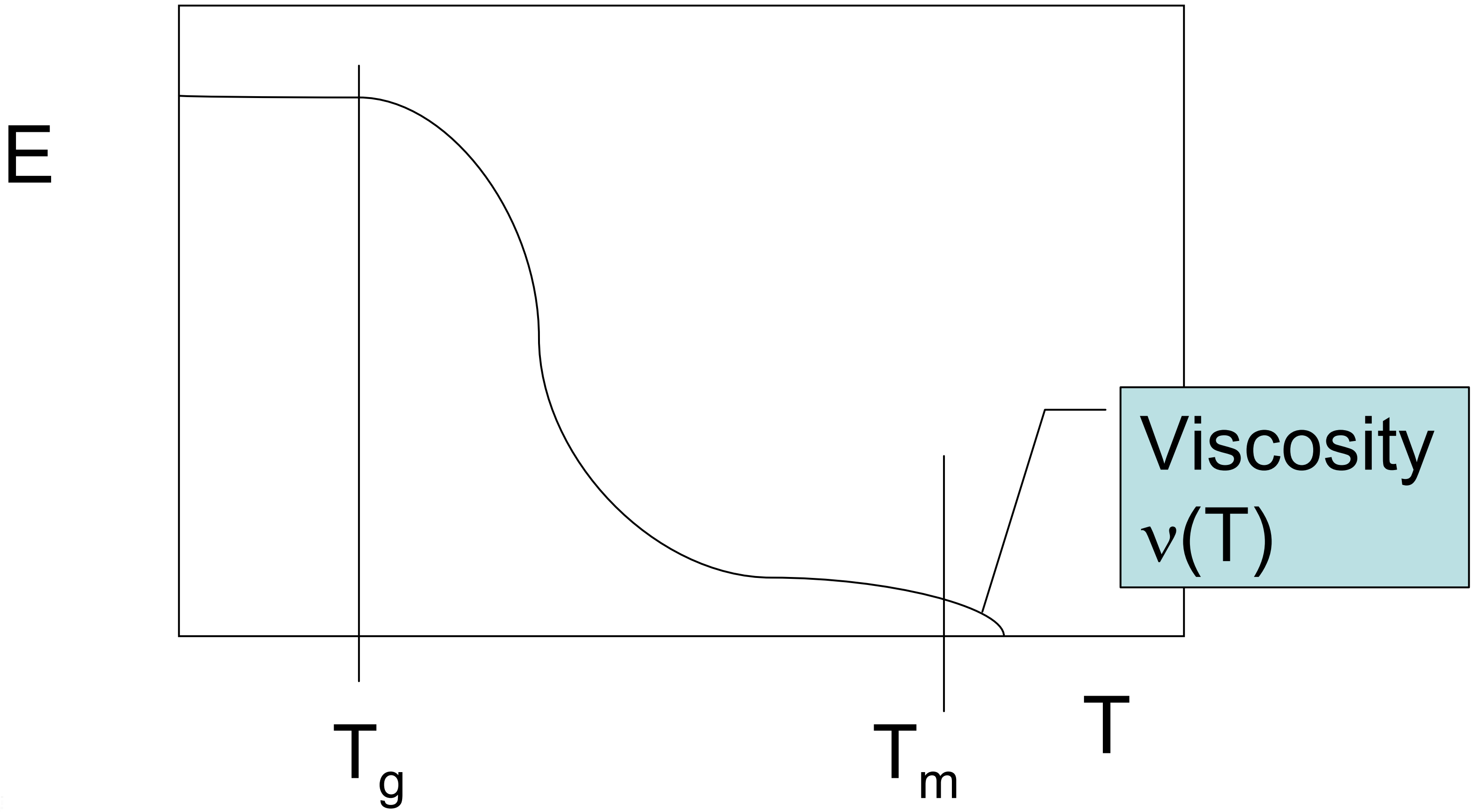
Geometry Determinants

- Mold Shape
- Material Shape Change upon Cooling
  - Residual Stress Effect
  - Thermal Expansion or contraction
- Extent of Mold Filling



Key Material Properties:
Flow into Mold

$$P = R(\nu)\ Q$$



Viscosity $\nu(T)$

Effect of Temperature on Flow

$Q = P/R$ R = resistance to flow $\alpha\ \nu$

$$\nu(T) = Ae^{ER(T_o - T)}$$

where:

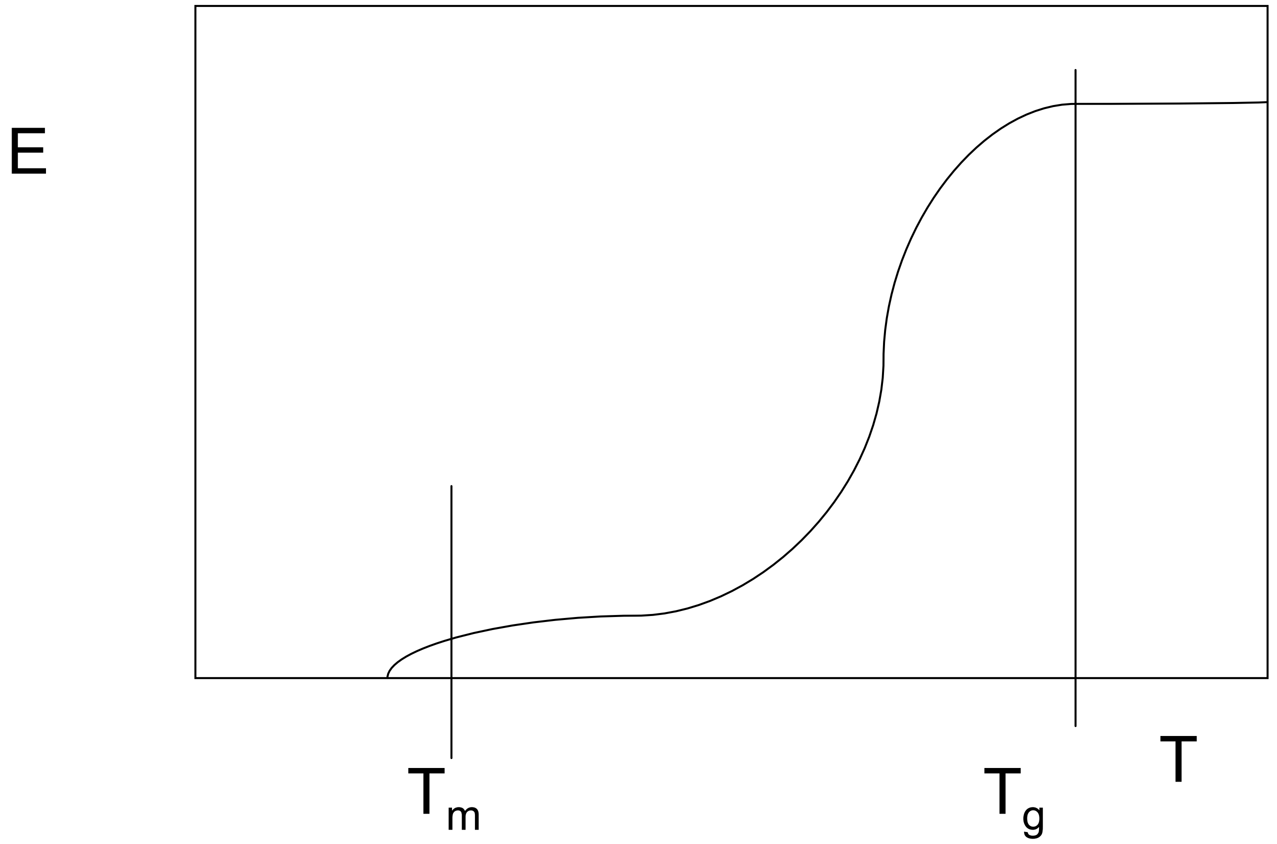
T = temperature

R = gas constant

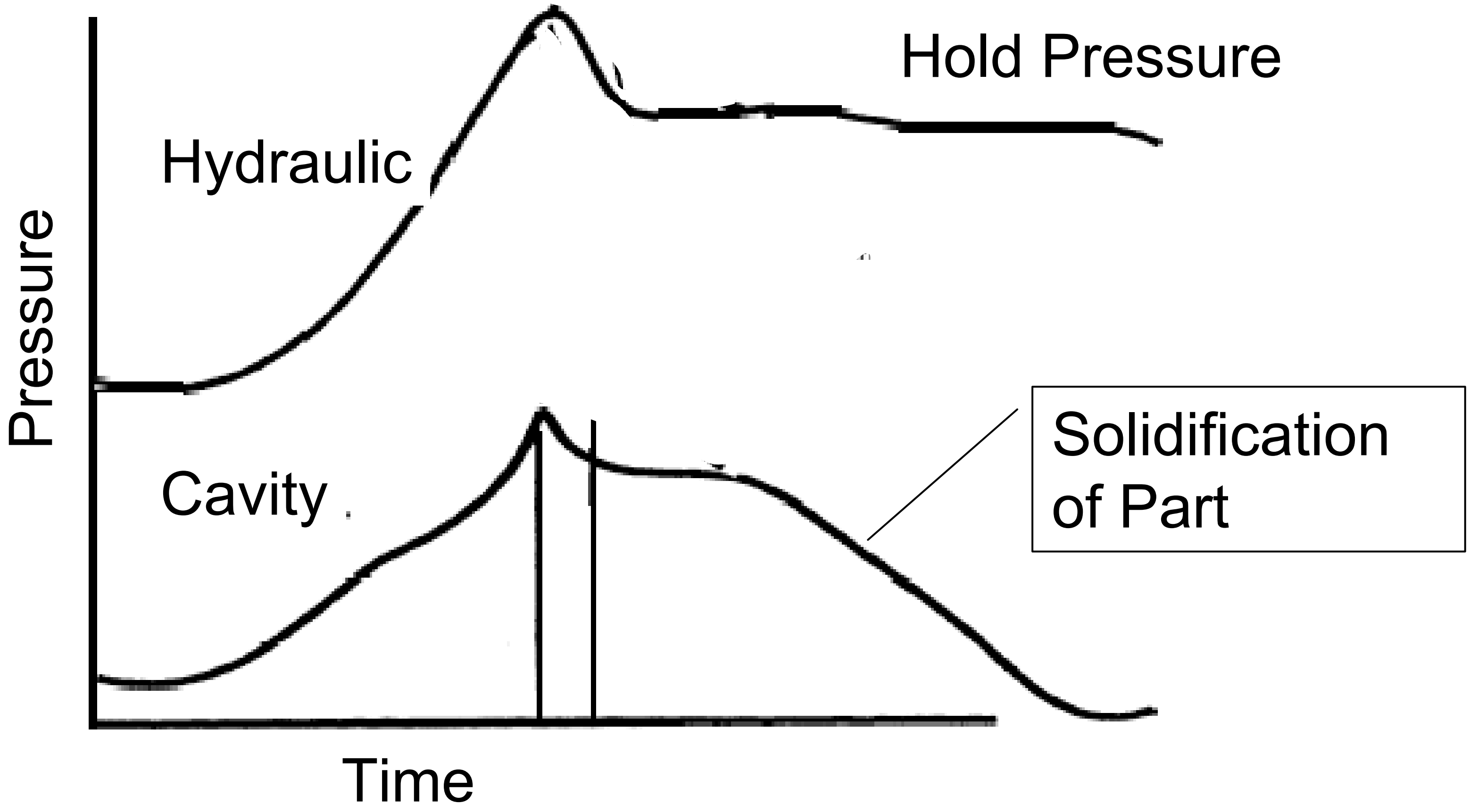
E = activation energy for viscosity

Key Material Properties:

Cooling



Packing Phase



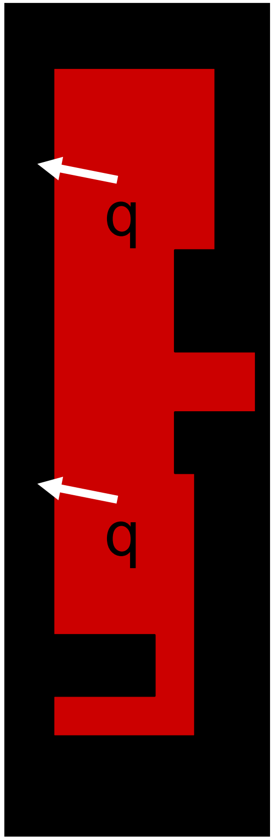
Solidification of Part

Heat Transfer: Filling

- $T_{part} > T_{mold}$ therefore always cooling
- Interior hotter than surface
- If T_{part} on surface $< T_g$ flow stops
  - Short Shot
- Viscosity is strong function of Temperature

Heat Transfer in the Mold

- $q = k A \partial T/\partial x$
  - – Rate decreases as $\partial T/\partial x$ decreases
    - Mold heat & polymer cools
- $dT/dt = \alpha \partial T^2/\partial x^2$
  - – $\alpha = k / \rho C_p$
    - Polymers have low k and high Cp



Process Control Issues

- Control Change in Shape upon Cooling
  - Consistent Mold Filling
  - Consistent Mold Pressure
    - Consistent Residual Stresses
  - Consistent Thermal environment
    - Consistent Thermal Distortion

Typical Equipment Control Systems

- Injection Velocity or Injection Pressure
- Nozzle Temperature
- Mold Temperature
- Barrel Heater Temperature

Equipment States

Sources of Variation

- Material Properties
  - Flow Properties
    - $\nu(T)$ relationship (especially if moist)
  - Thermal properties (ditto)
  - Also effects of "regrind"

Example: Effect of Blending

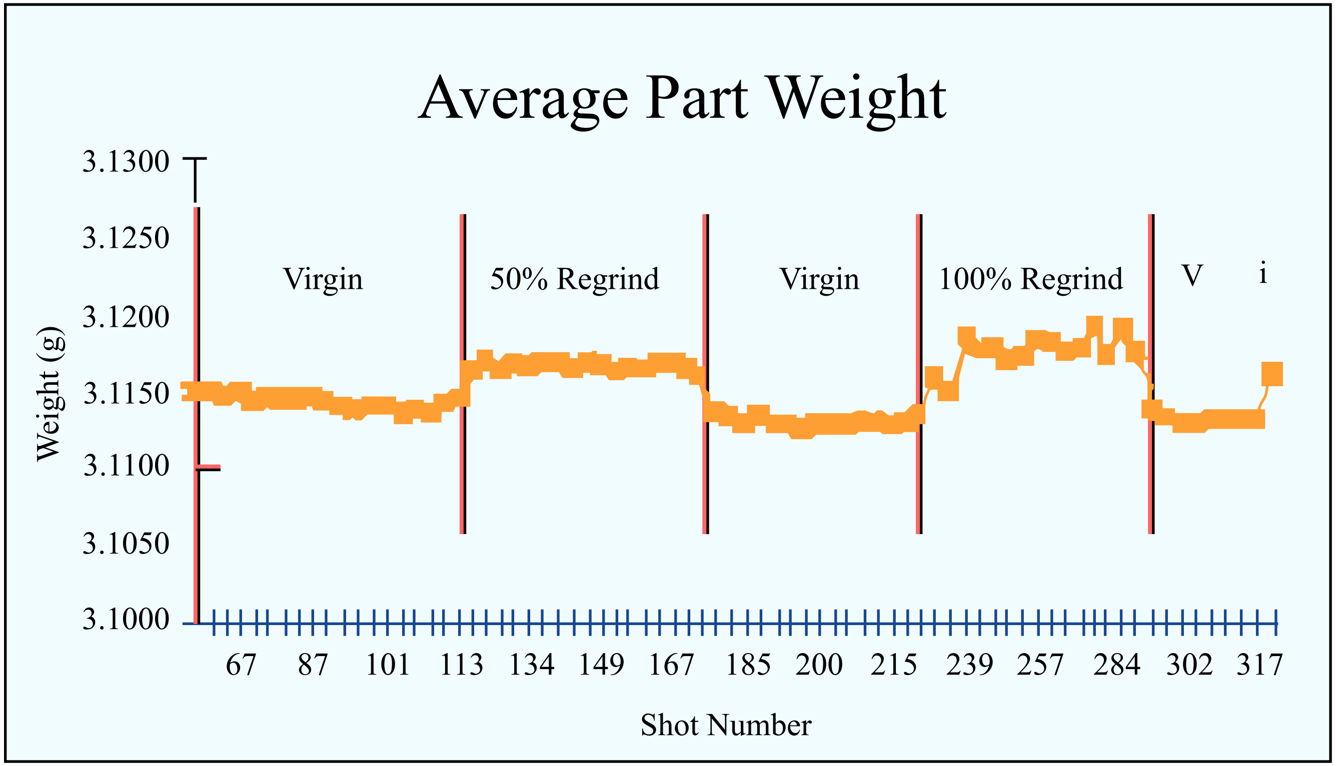
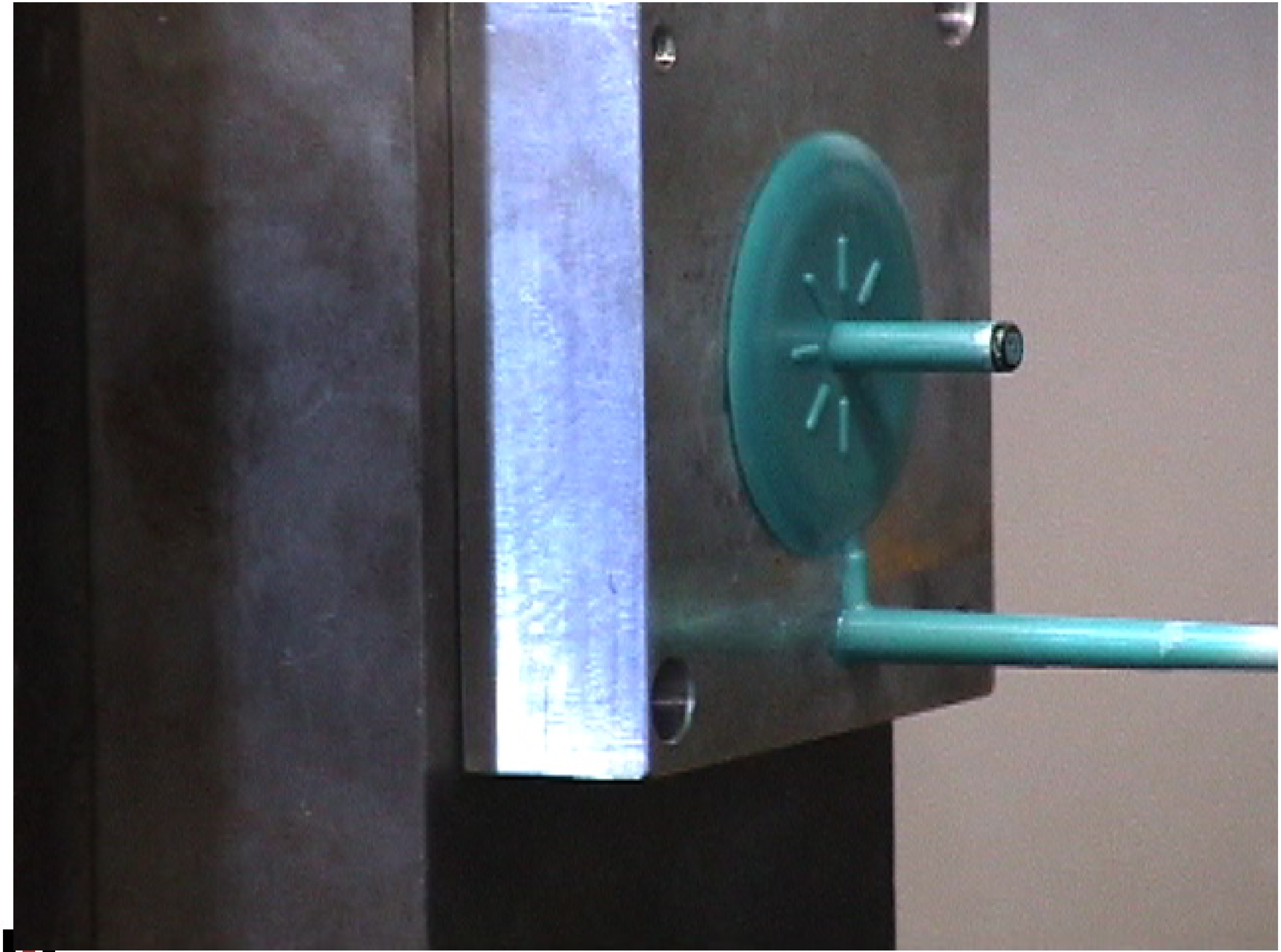
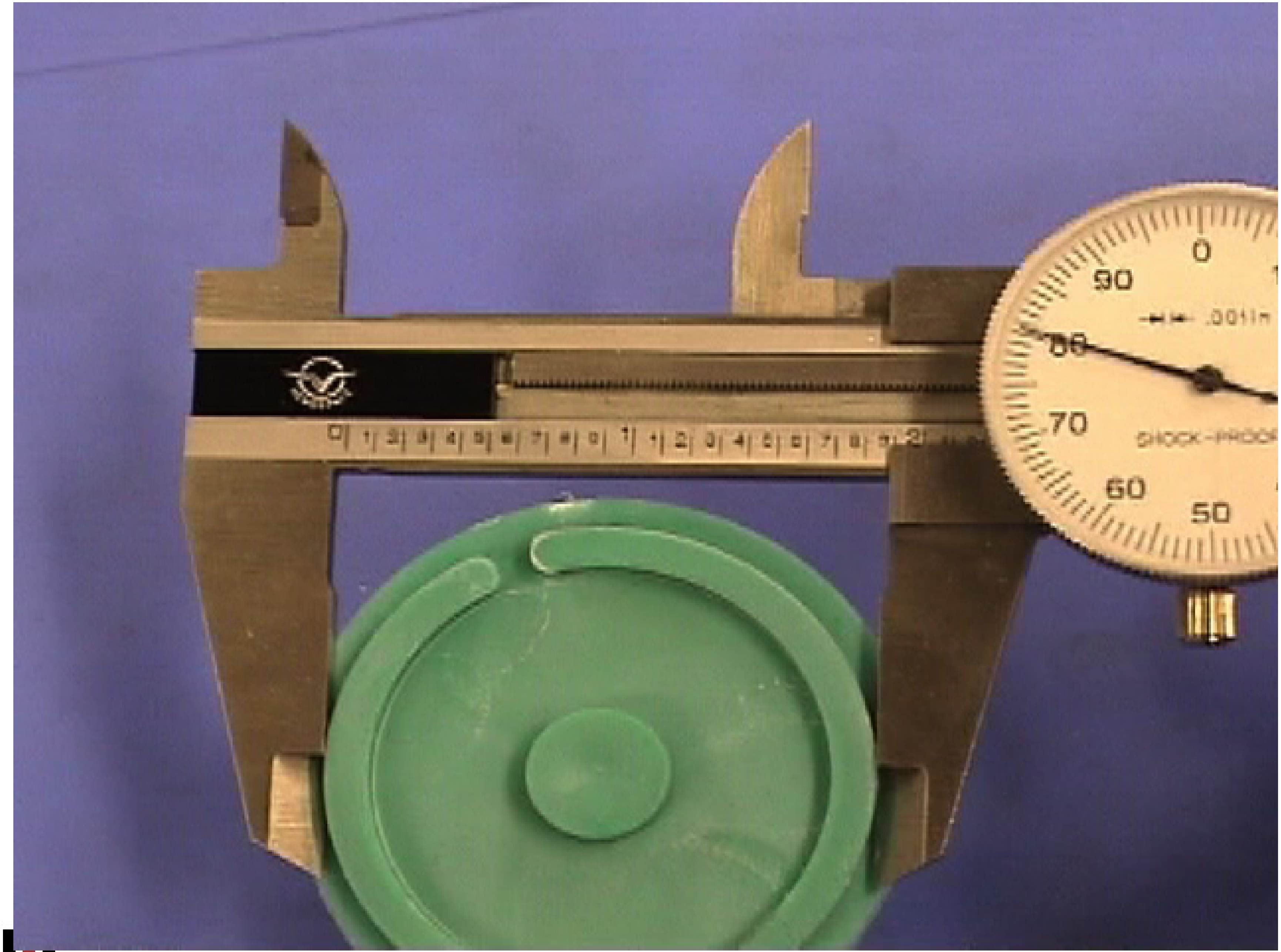


Figure by MIT OpenCourseWare.

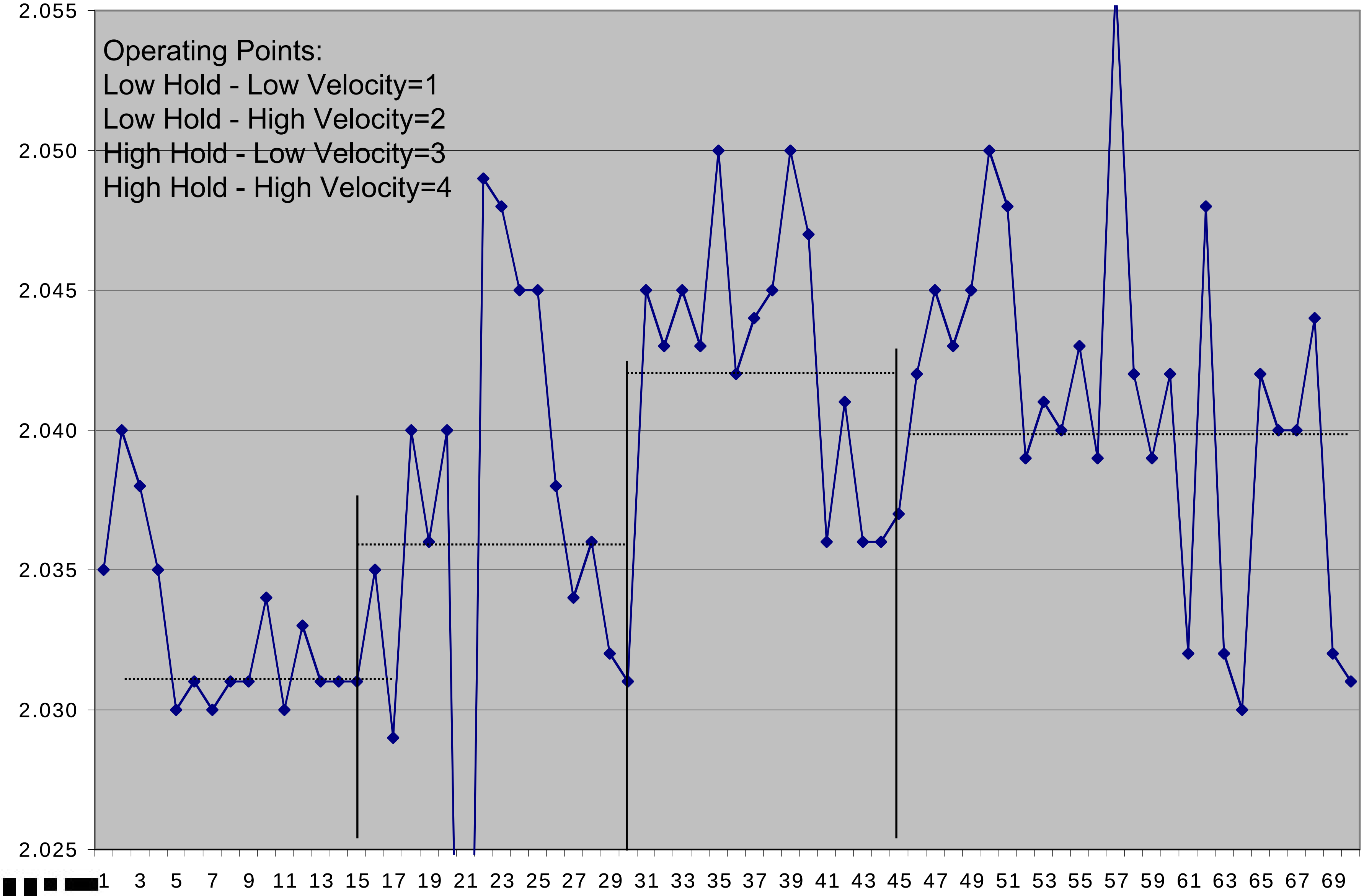
Lab Data

- Variable Hold Time
- Variable Injection Velocity

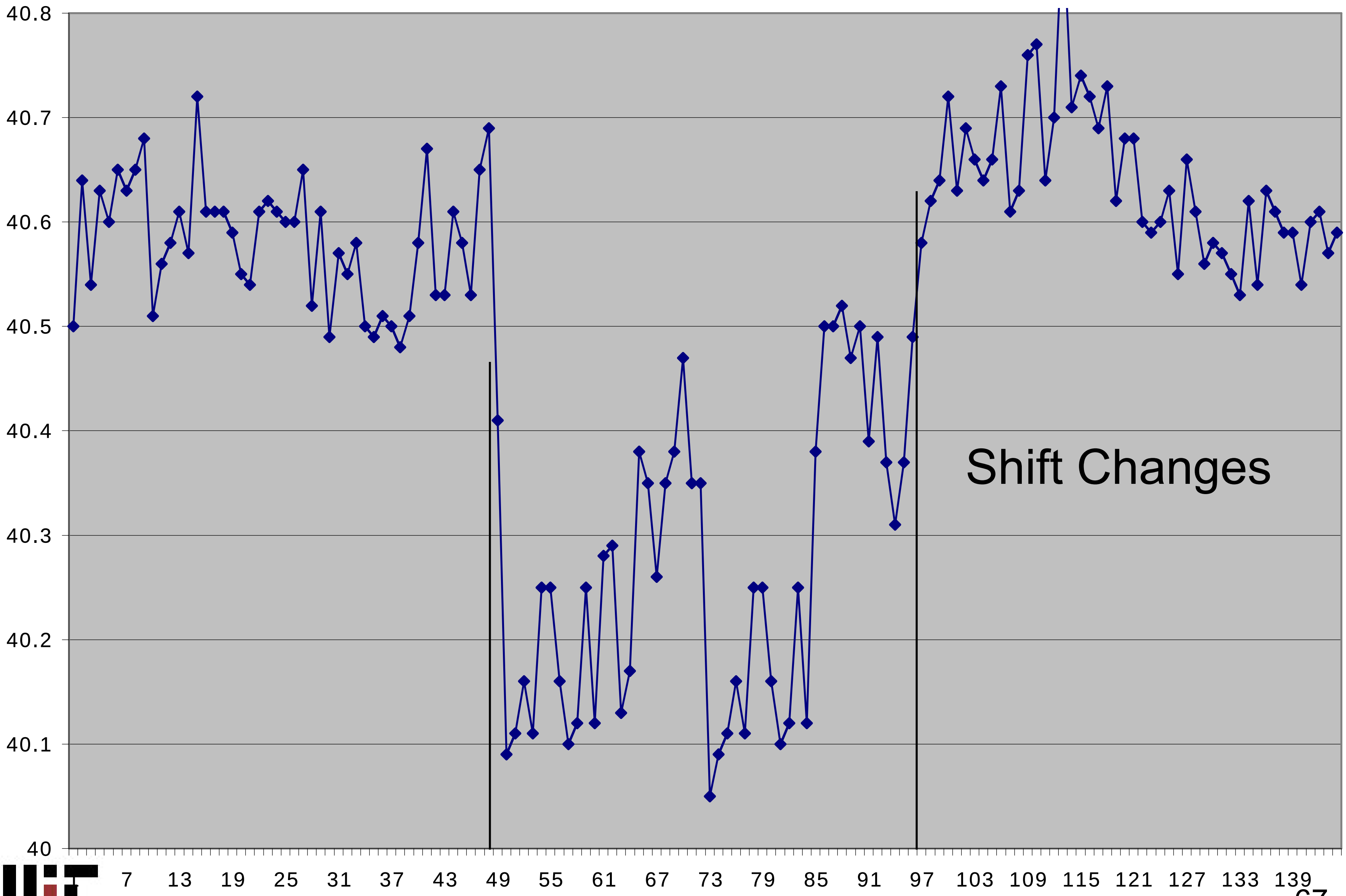



0
90
.001in
80
70
SHOCK-PROOF
60
50
0 1 2 3 4 5 6 7 8 9 1 1 2 3 4 5 6 7 8 9 2

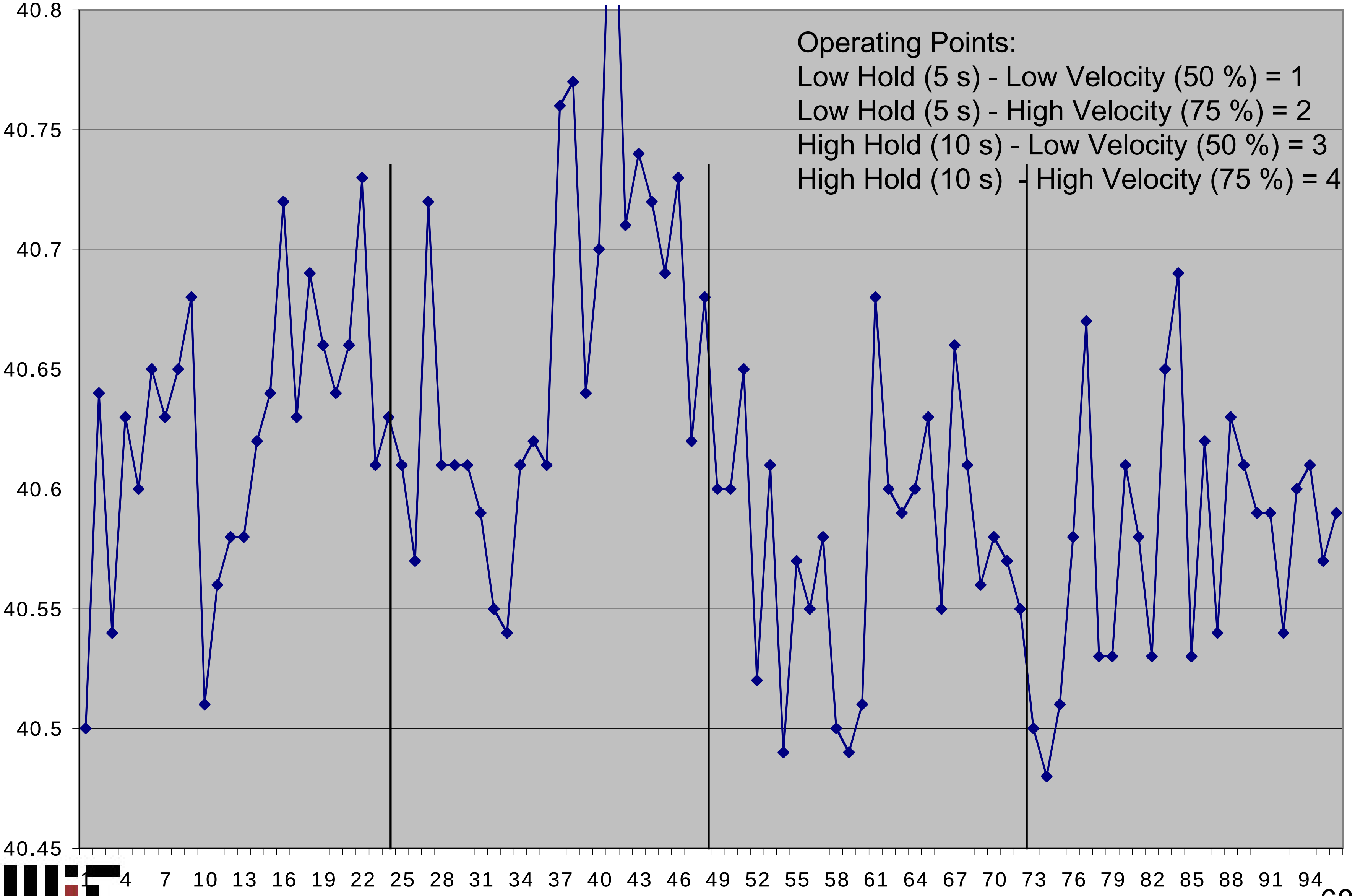
Injection Molding Data



Injection Molding NTU



I.M. NTU (no Group 1)



Operating Points:
Low Hold (5 s) - Low Velocity (50 %) = 1
Low Hold (5 s) - High Velocity (75 %) = 2
High Hold (10 s) - Low Velocity (50 %) = 3
High Hold (10 s) - High Velocity (75 %) = 4

Sources of Variation

- Equipment Properties
  - Heat Transfer Properties
  - Mold Flow Passages
- Equipment States
  - Barrel and Nozzle Temperatures
  - Mold Temperatures
  - Flow Rates
  - Packing Pressure

Conclusions

- I.M. is a Complex, Parallel Formation Process
- Strong Dependence on Material Properties
  - Viscosity sensitivity
  - Heat Transfer Sensitivity
- Thermal State Must be Well Controlled
  - Many opportunities on the equipment
  - Material State very hard to do
    - Distributed
    - Interference with Process

Conclusions: Variation

$$\Delta Y = \frac{\partial Y}{\partial \alpha}\Delta \alpha \quad + \frac{\partial Y}{\partial u}\Delta u$$

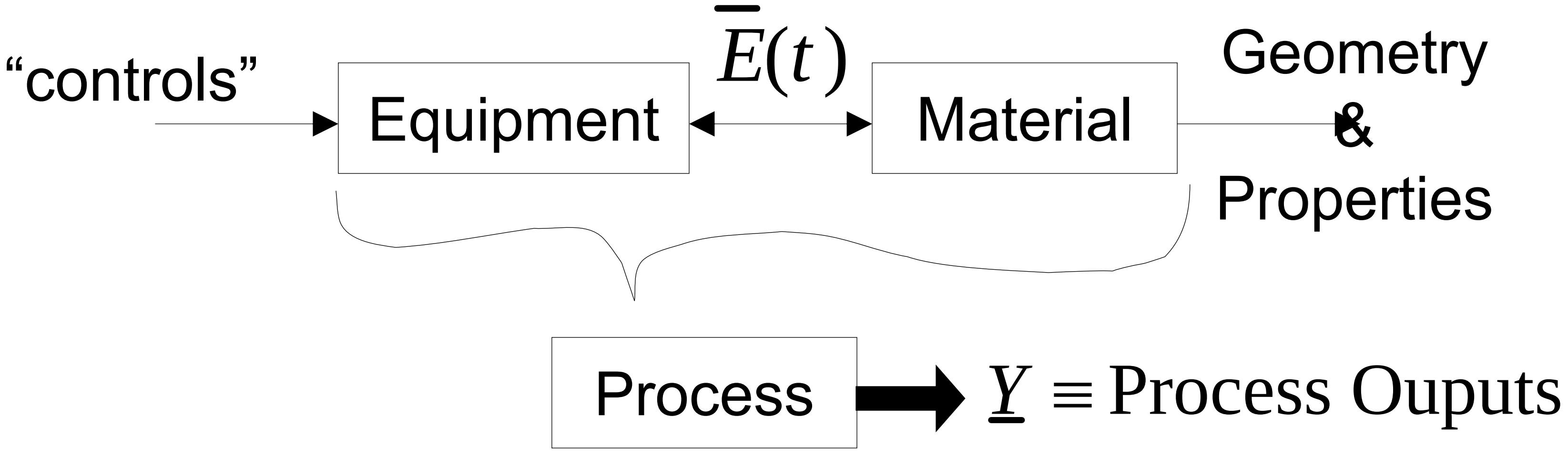
Disturbances

- Equipment Property Changes
- Material Property Changes
- Material State Uncertainty
- Equipment State Uncertainty

Control Inputs:

- Equipment States

Process Model for Control



"controls"

Equipment

$\bar{E}(t)$

Material

Geometry & Properties

Process

$\underline{Y} \equiv \text{Process Ouputs}$

$$\underline{Y} = \Phi(\underline{\alpha})$$

$$\underline{\alpha} \equiv \text{process } \textit{parameters}$$

What are the α's?

What *are* the *Process Parameters*?

- Equipment Energy “States”
- Equipment Constitutive “Properties”

- Material Energy “States”
- Material Constitutive ”Properties”

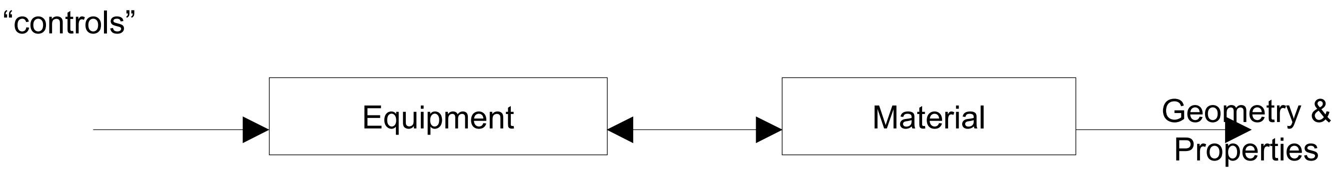
Energy States

Energy Domain	Energy or Power Variables
Mechanical	F, v ; P, Q or F, d ; σ, ε
Electrical	V, I
Thermal	$T, ds/dt$ (or dq/dt)
Chemical	chemical potential, rate

Properties

- *Extensive*: GEOMETRY
- *Intensive*: Constitutive Properties
  - Modulus of Elasticity, damping, mass
  - Plastic Flow Properties
  - Viscosity
  - Resistance, Inductance, Capacitance
  - Chemical Reactivity
  - Heat Transfer Coefficient
- Which has the highest precision?

A Model for Process Variations



“controls”

Equipment

Material

Geometry & Properties

- Recall:

$$\underline{Y} = \Phi(\underline{\alpha})$$

- One or more α’s “qualify” as inputs : $\underline{u}$

$$\underline{Y} = \Phi(\underline{\alpha}, \underline{u}); \qquad \underline{u} = \text{vector of inputs}$$

- The first order Variation ΔY gives the “Variation Equation”

The Variation Equation

$$\Delta Y = \frac{\partial Y}{\partial \alpha}\Delta \alpha + \frac{\partial Y}{\partial u}\Delta u$$

Disturbance Sensitivity

Disturbances

Control Sensitivity or “Gain”

Control Inputs

Primary Process Control Goal: Minimize ΔY

How do we make $\Delta Y \rightarrow 0$?

$$\Delta Y = \frac{\partial Y}{\partial \alpha}\Delta\alpha + \frac{\partial Y}{\partial u}\Delta u$$

- hold *u* fixed ($\Delta u = 0$)
  - operator training (SOP's)
  - good steady-state machine physics
- minimize disturbances
  - ☐ $\Delta\alpha$ ->$\Delta\alpha_{min}$

This is the goal of Statistical Process Control (SPC)

OR

$$\Delta Y = \frac{\partial Y}{\partial \alpha}\Delta\alpha \quad + \frac{\partial Y}{\partial u}\Delta u \qquad\qquad \Delta Y \to 0$$

- hold u fixed ($\Delta \underline{u}$ = 0)
- minimize the term: $\frac{\partial Y}{\partial \alpha}$ the disturbance sensitivity

This is the goal of Process Optimization

- **Assuming** $\frac{\partial Y}{\partial \alpha} = \Phi(\underline{\alpha})$ $\underline{\alpha}$ **= operating point**

OR

$$\Delta Y = \frac{\partial Y}{\partial \alpha}\Delta\alpha \quad + \frac{\partial Y}{\partial u}\Delta u \qquad\qquad \Delta Y \to 0$$

- manipulate $\Delta \underline{u}$ *by measuring ΔY such that*

$$\Delta u \frac{\partial Y}{\partial u} = -\frac{\partial Y}{\partial \alpha}\Delta\alpha$$

This is the goal of Process Feedback Control

•Compensating for (not eliminating) disturbances

Statistical Process Control

$$\Delta Y = \frac{\partial Y}{\partial \alpha}\Delta\alpha + \frac{\partial Y}{\partial u}\Delta u$$

Detect
and
Minimize

Process Optimization

$$\Delta Y = \frac{\partial Y}{\partial \alpha}\Delta \alpha + \frac{\partial Y}{\partial u}\Delta u$$

Empirically Minimize

Output Feedback Control

$$\Delta Y = \frac{\partial Y}{\partial \alpha}\Delta \alpha + \frac{\partial Y}{\partial u}\Delta u$$

$$\frac{\partial Y}{\partial u}\Delta u = -\frac{\partial Y}{\partial \alpha}\Delta \alpha$$

Manipulate Actively Such that

Compensate for Disturbances

Process Control Hierarchy

- Reduce Disturbances
  - Good Housekeeping
  - Standard Operations (SOP's)
  - **Statistical Analysis and Identification of Sources (SPC)**
  - **Feedback Control of Machines**
- Reduce Sensitivity (increase "Robustness")
  - **Measure Sensitivities via Designed Experiments**
  - Adjust "free" parameters to minimize
- Measure output and manipulate inputs
  - **Feedback control of Output(s)**