Cost Analysis and Estimating
for Engineering and Management

Chapter 7
Operation Estimating

Overview

- Find Time/Cost for Production Steps
- Determine Direct Labor Time
- Look at a Metal Machining Example
  - Set Up
  - Cycle Time
- One Time Tooling Costs
- Overview of Flow Line Manufacturing

Background

- "Design" Defines a Part
- Design Is Broken Down into Operations
- Labor & Material Determined
- Cost Estimated

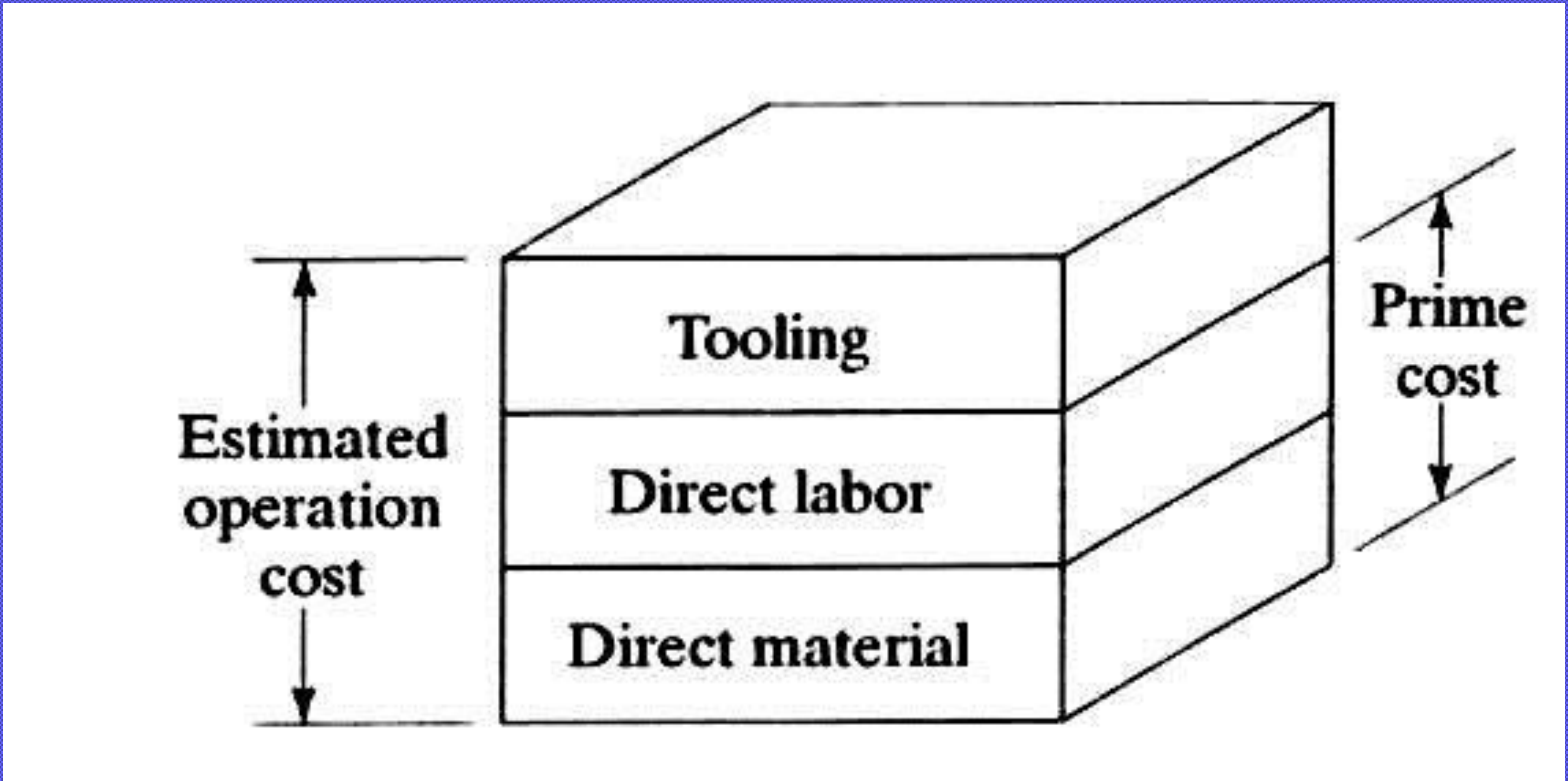
Definitions

- Manufacturing Operations
  - –Produce Changes to Objects to Increase Value
- Cost
  - –For Utilization of Labor & Materials to Increase Value of Some Object

Operation Estimates

- Establish Costs for Components and Assemblies
- Initiate Cost Reductions
- Provide Standards
- Compare Different Designs
- Support Decisions

Operation Cost Elements



Industries

- Construction

Plant and Equipment	Output of Industry	Value of Output
Portable	Immobile and unique	Expensive

Industries

- Agriculture

Plant and Equipment	Output of Industry	Value of Output
Mobile	Moves off the plant site and is numerous	Inexpensive

Industries

- Information and Service

Plant and Equipment	Output of Industry	Value of Output
Transitional	Temporary	Low priced

Industries

- Manufacturing

Plant and Equipment	**Output of Industry**	**Value of Output**
Fixed	Moves off the plant site and is numerous	Cheap to expensive

Manufacturing Facts

- Average Lot Quantity - 100 Units
- Employs 16% of Population
- Declining as a Percentage
- Still Increasing in Absolute Numbers
- Productivity Is Exceedingly High

Discrete Manufacturing

- Mass Production
  - –High Volume, Independent of Orders
- Moderate Production
  - –Large Volume, Connected to Orders, Fluctuates
- Job Lot
  - –Small Quantities (1-500)

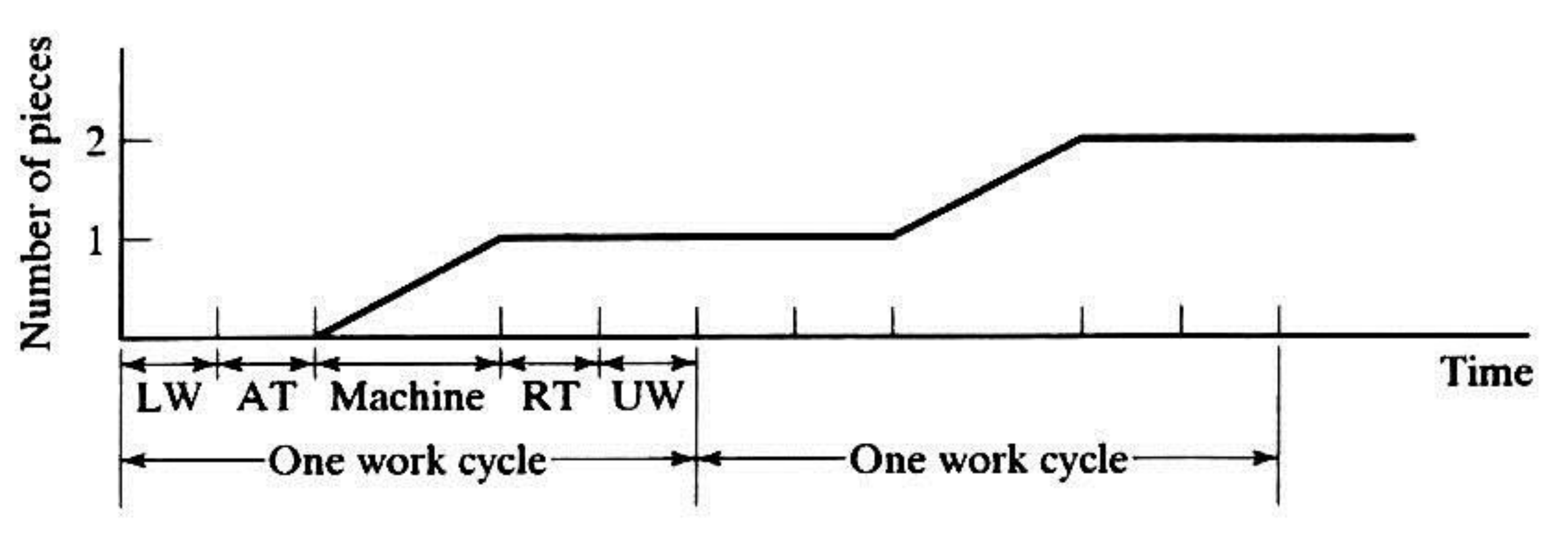
Operation

- Series of Elements
- Performed at a Single Workstation
  - Machine, Bench, Process
- One or More Operations to Complete a Part or Assembly to a Predetermined State (per Drawing/Design)

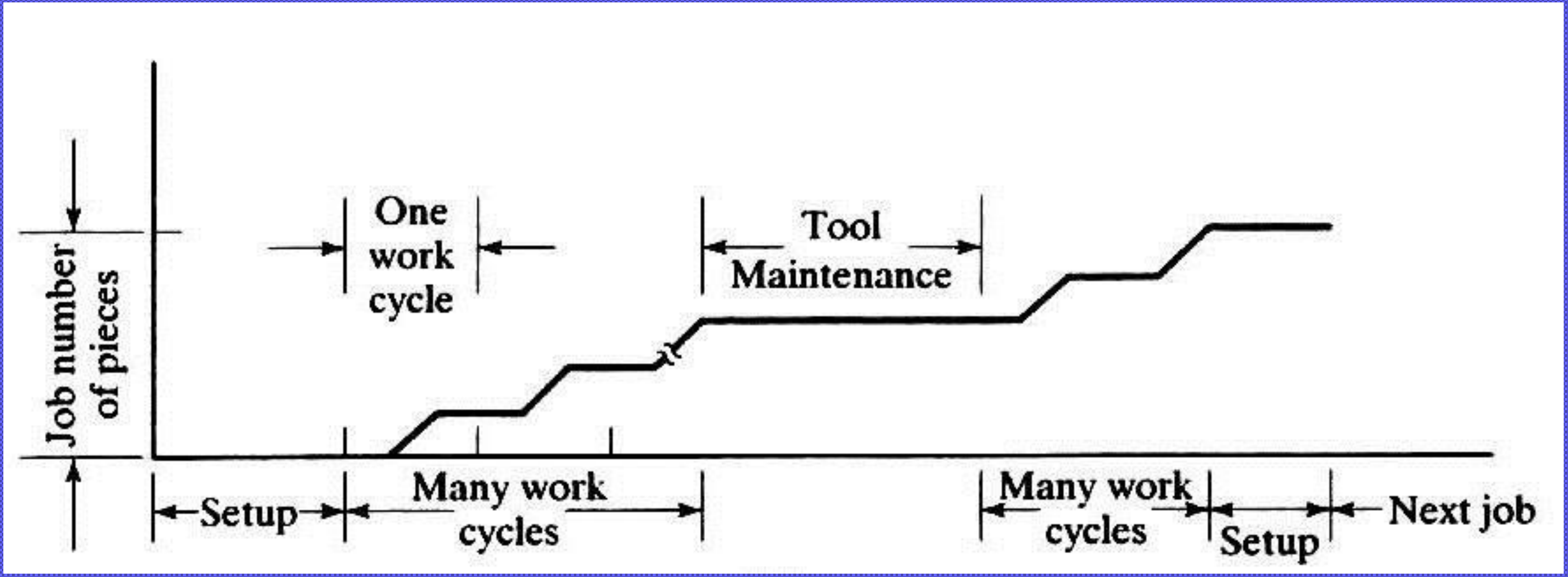
Machining

- Traditional Metal Cutting
- Subject for Remaining Discussion
- Set Up
  - –Prepare Machine/Process
  - –Includes Return to Neutral Condition
- Cycle time
  - –Run Time to Complete One Unit
  - –Repeats

Classic Operations Analysis



Classic Operations Analysis



Modeling Machining Time

- Single Point Tool - Turning Operation
- Time (Cost) Is Function of:
  - Handling Time
  - Machining Time
  - Tool Changing Time
  - Tool Cost

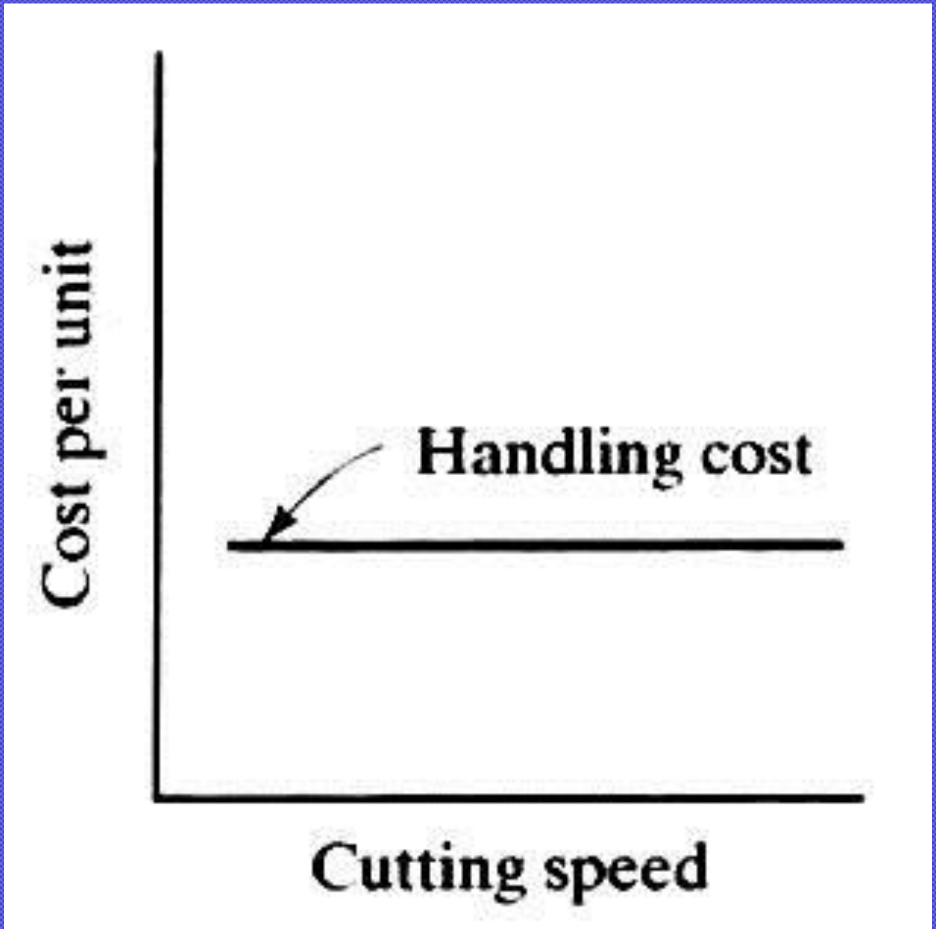
Handling Cost

- Load and Unload Work
- Constant
- Not Related to Cutting Time

$$\text{handling cost} = C_o t_h$$

Eq 7.1

Handling Cost



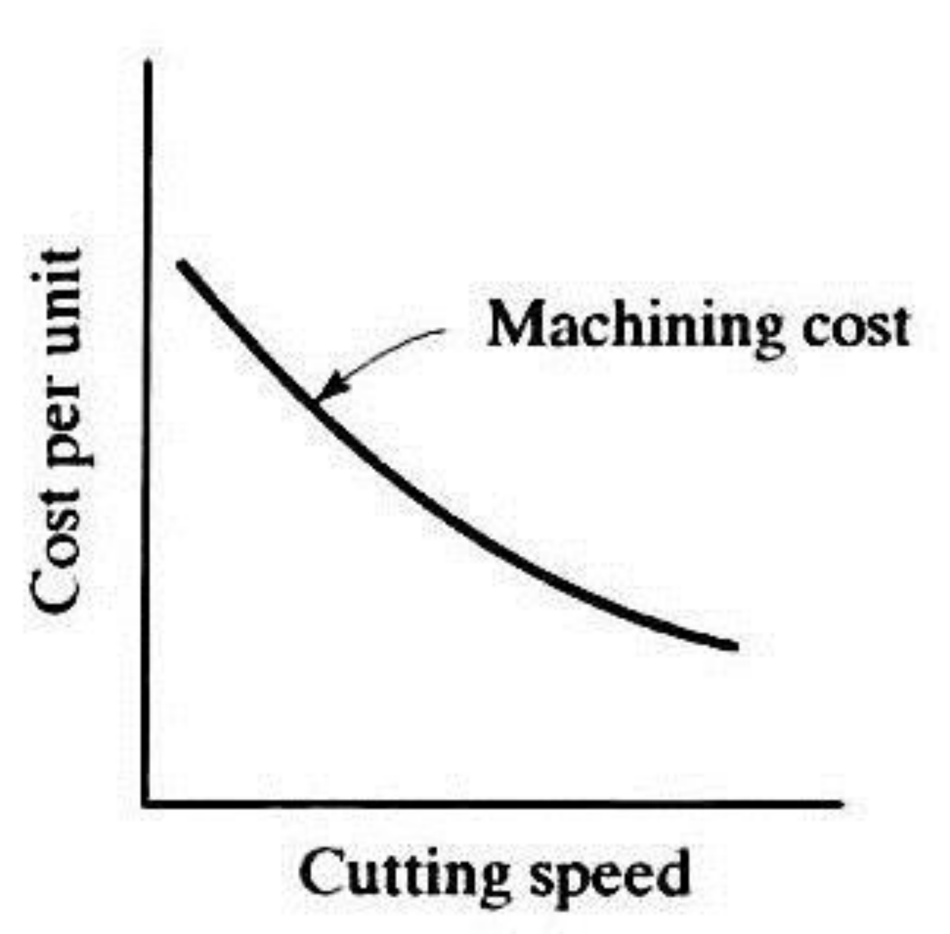
Machining Cost

- Based on Cutting Speed and Feed
- Controlled by Machine Setting
- Shape of Part Is Changed

$$t_m = \frac{L}{fN} = \frac{L\pi D}{12Vf} \qquad \text{Eq 7.2}$$

$$\text{machining cost} = C_o t_m \qquad \text{Eq 7.3}$$

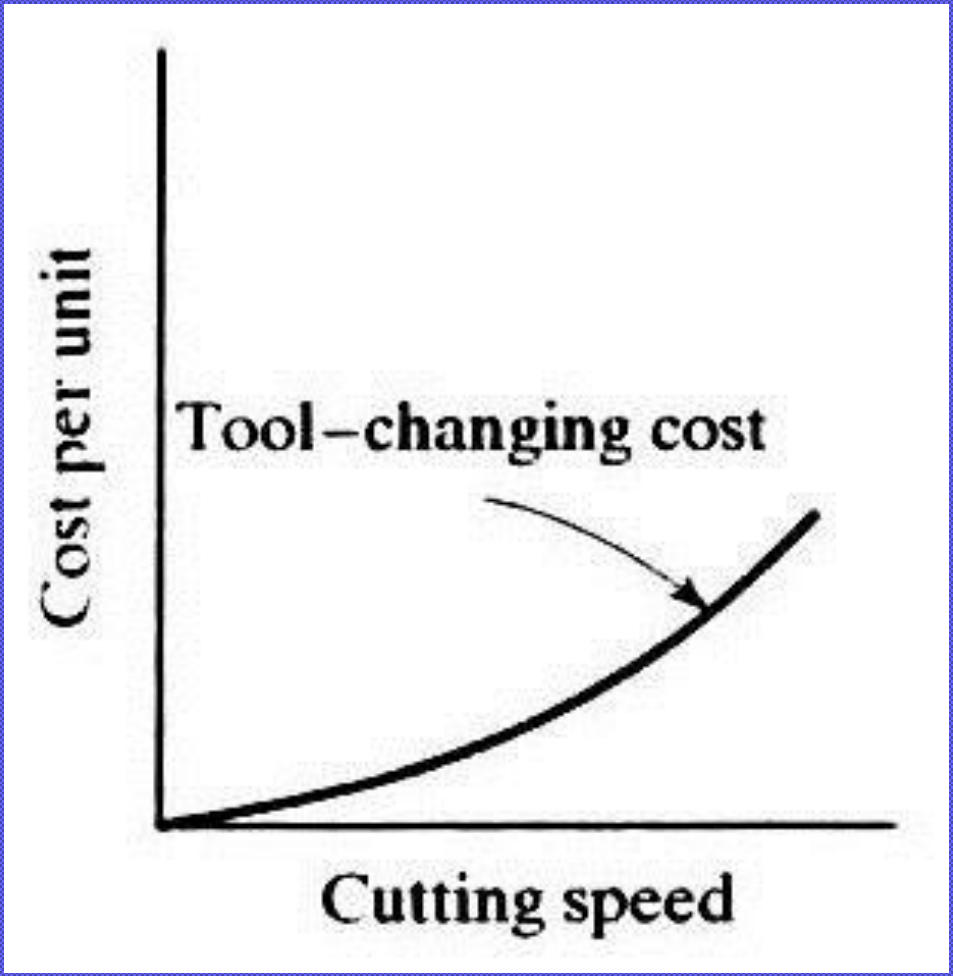
Machining Cost



Tool Associated Costs

- Tool Cutting Edges Wear
- Wear Rate Increases with Speed
- Tools Need to be Replaced/Sharpened
- Takes Operator's Time
- Apportioned Over Parts Produced

Tool Changing Cost



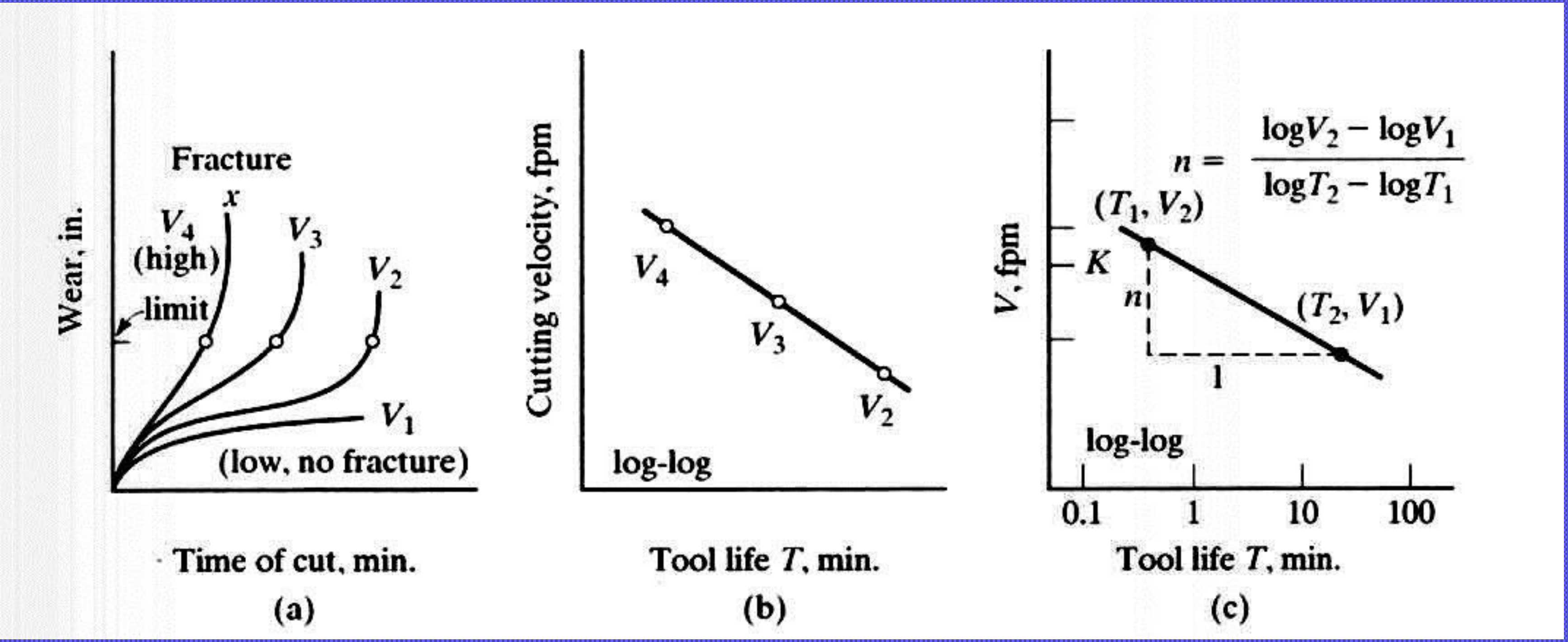
Tool Life

- Taylor's Tool Life Equation

$$VT^n = K$$ Eq 7.6

- Relates Tool Life to Cutting Speed
- Constants Empirically Determined
  - For a Given Set of Conditions Only

Determining *n* and *K*



Apportioning the Tool Costs

- Determine Fraction of the Tool Life Used Up on Each Part

$$t_m / T$$

- Tool Changing Cost / Part

$$\text{perishable tool changing cost} = C_o t_c \left(\frac{t_m}{T}\right) \qquad \text{Eq 7.7}$$

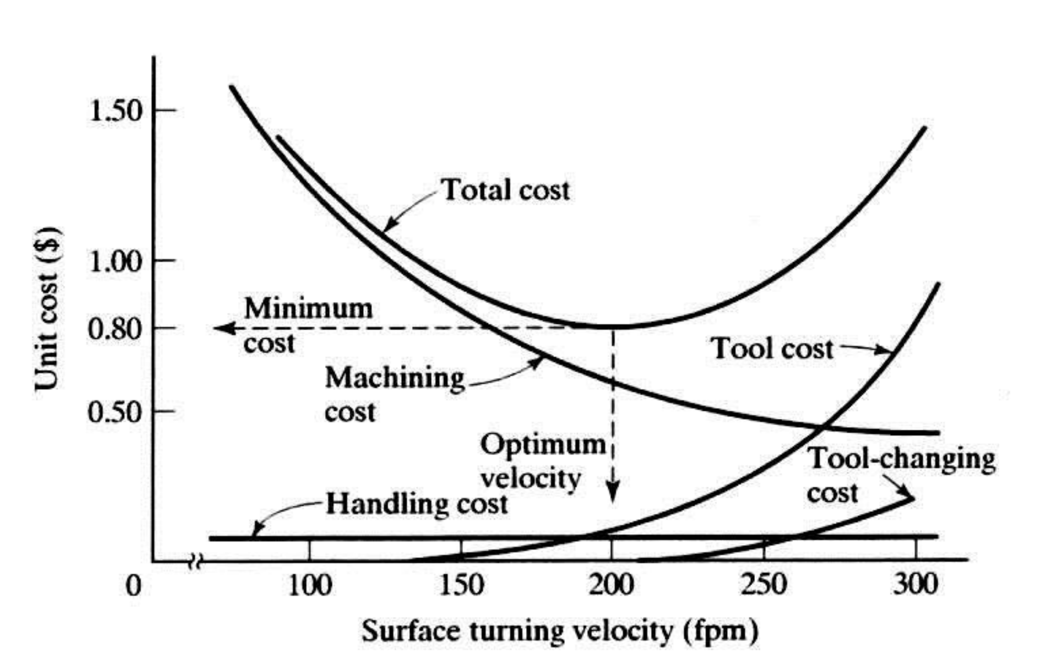
- Tool Cost / Part

$$\text{perishable tool cost} = C_{pt} \left(\frac{t_m}{T}\right) \qquad \text{Eq 7.8}$$

Total Machining Time / Part

$$C_u = \sum \left[C_o t_h + \frac{t_m}{T}(C_{pt} + C_o t_c) + C_o t_m \right]$$

Eq 7.9



Finding Optimum Cost / Time

- Minimum Machining Cost

$$V_{\min} = \frac{K}{\left[\left(\frac{1}{n}-1\right)\left(\frac{C_o t_c + C_{p_t}}{C_o}\right)\right]^n}$$

Eq 7.10

Maximum Production Output

– Ignore Tool Cost - Minimize Time

$$V_{\max} = \frac{K}{\left[\left(\frac{1}{n}-1\right) t_c\right]^n}$$

Eq 7.12

Operations Analysis

- Determine
  - –Production Quantity
  - –Operations
- Divide Operations into Elements
- Determine Element Times
  - –For Set Up and Cycle
  - –From Data Warehouse
  - –Add Element Times to Get Operation Time

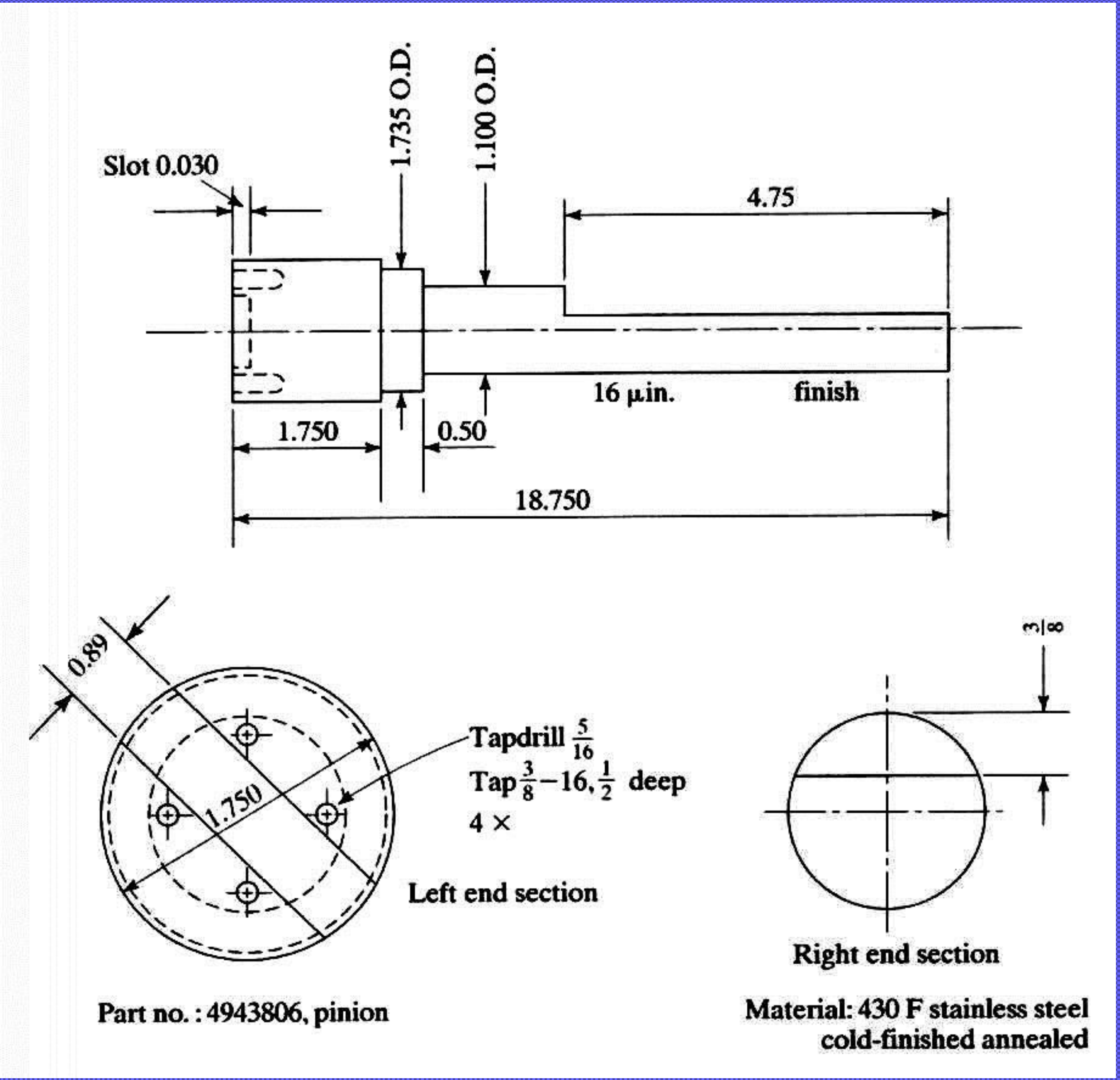
Operations Sheet

- Divides Manufacturing Process into Operations
- Specifies:
  - Machines/Locations
  - Sequence
  - Work to Be Done in Each Operation

Steps for Operations Sheet

- Interpret Engineering
- Select Work Locations/Equipment
- Specify Tools
- Partition into Distinct Operations
- Describe Each Operation
- Present Information

Example Part



Example Operations Sheet

- Initial Operations Sequence

Workstation	Op No.	Description
Turret lathe	10	Turn and cutoff
Vertical mill	20	End mill slot
Horizontal mill	30	Slab mill flat
NC drill press	40	Drill and tap holes

Operations Process Plan

Workstation	Op. no.	Description of operation	Setup hr	Cycle hr/100	Lot hr
Turret lathe	10	Face 0.015			
		Turn rough 1.45			
		Turn rough 1.15			
		Finish turn 1.10			
		Turn 1.735			
		Cutoff to 18.75			
Vertical mill	20	End mill 0.89 slot			
Horizontal mill	30	Slab mill 4.75 x 3/8			
N.C. turret drill	40	Drill, tap			

Set Up

- Once per Lot
- Given in Hours
- Select Appropriate

Elements

Description	Hr
Punch in and out, study drawing	0.2
Turning Equipment	
First tool	1.3
Each additional tool	0.3
Collet	0.2
Chuck, fixture	0.1

Handling Time

- Select Appropriate Elements
- Time in Minutes (Watch Units!)

Machine and Element Description	Min
Turning, milling, drilling	
Start and stop machine	0.08
Change speed of spindle	0.04
Inspect dimension with micrometer	0.30
Turning equipment	
Cross slide advance, return, and index	0.09
Advance stock through feed tube < 6”	0.18

Machining Time

- Majority of Cycle Time (Usually)
- Machine Driven (Cutting Feed Rate)
- Function of Design/Material
  - Amount of Material to Remove
  - Machine Tool(s) Used
  - Speeds and Feeds

Operation 10

- Set Up (from Table 7.4)

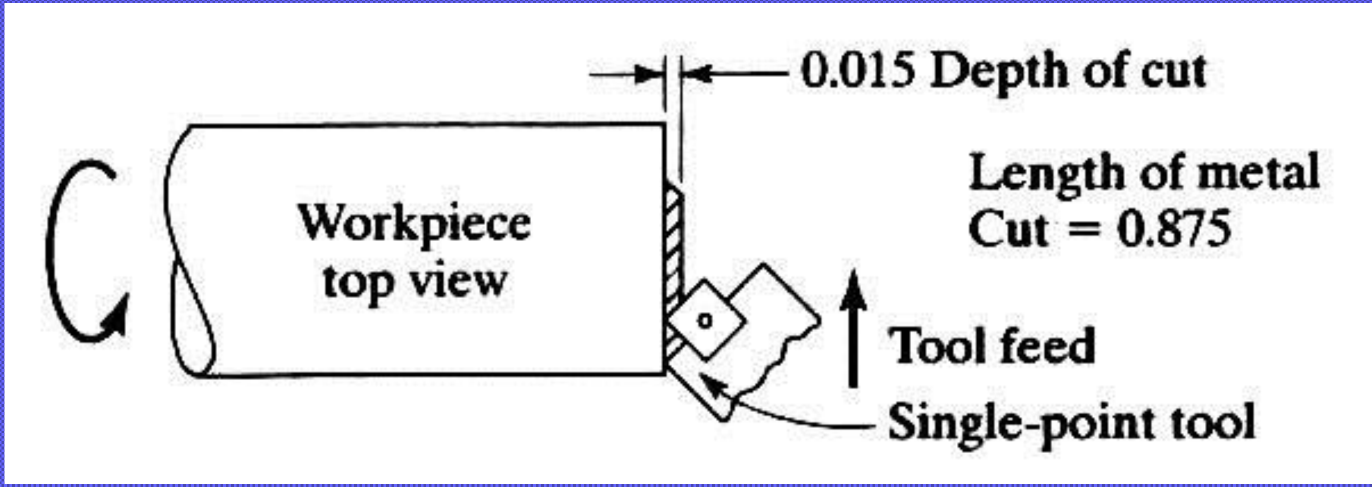
A. Setup elements	Hr
Punch in and out, study drawing	0.2
Collet	0.2
First facing tool	1.3
Additional 5 tools	1.5
Setup total, operation 10	3.2

Op 10 - Handling

- From Table 7.5

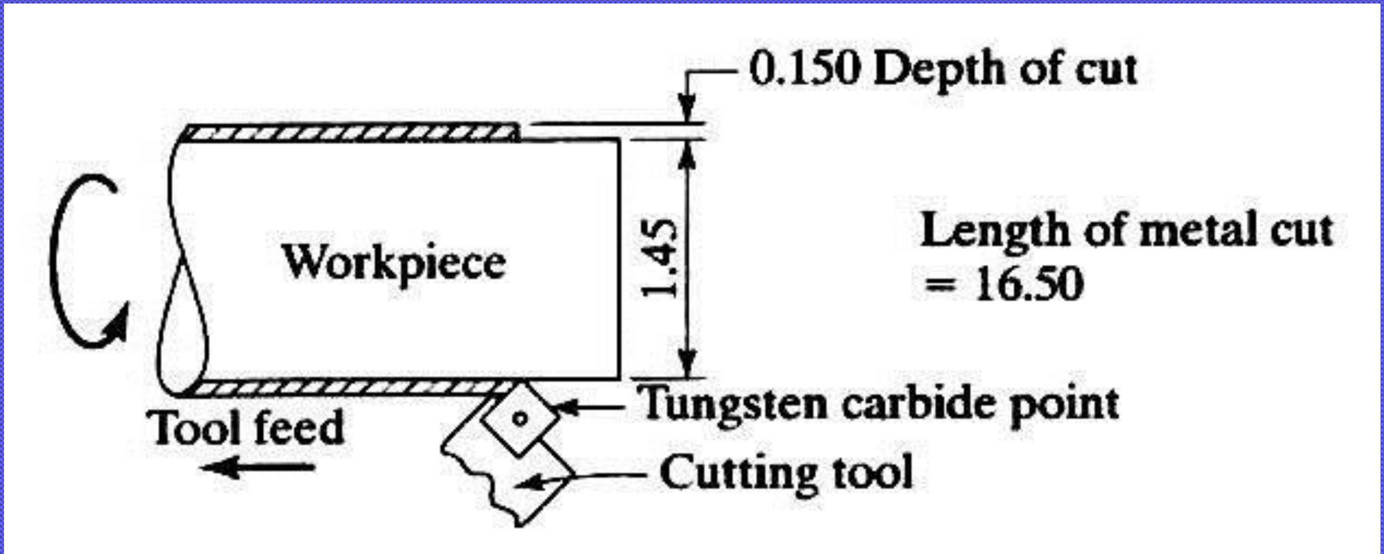
B. Handling	**Min**
Start and stop machine	0.08
Advance stock	0.37
Place and remove oil guard	0.19
Speed changes, assume 4 x 0.04	0.16
End turret 5 x 0.08	0.40
Cross slide advance, return	0.09
Inspect part with micrometer, irregular 1/5 x 0.30	<u>0.06</u>
Subtotal of handling and equipment elements	1.35

Facing



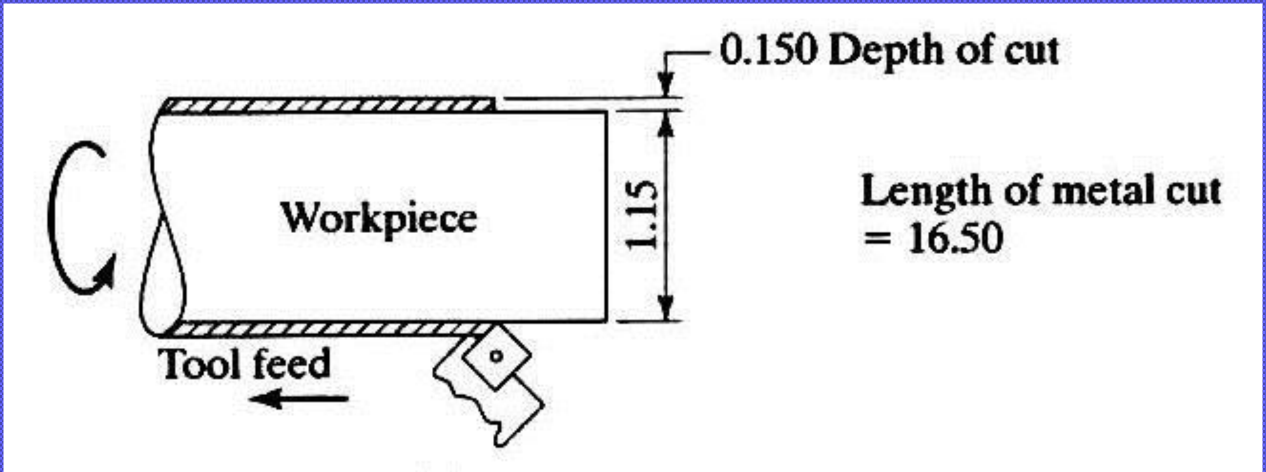
Elem	Depth of Cut	L_d	L_s	L	D	V fpm	F (ipr)	t_m, min
Face	0.015	0.875	1/32	.906	1.750	350	.007	0.17

First Rough Turn



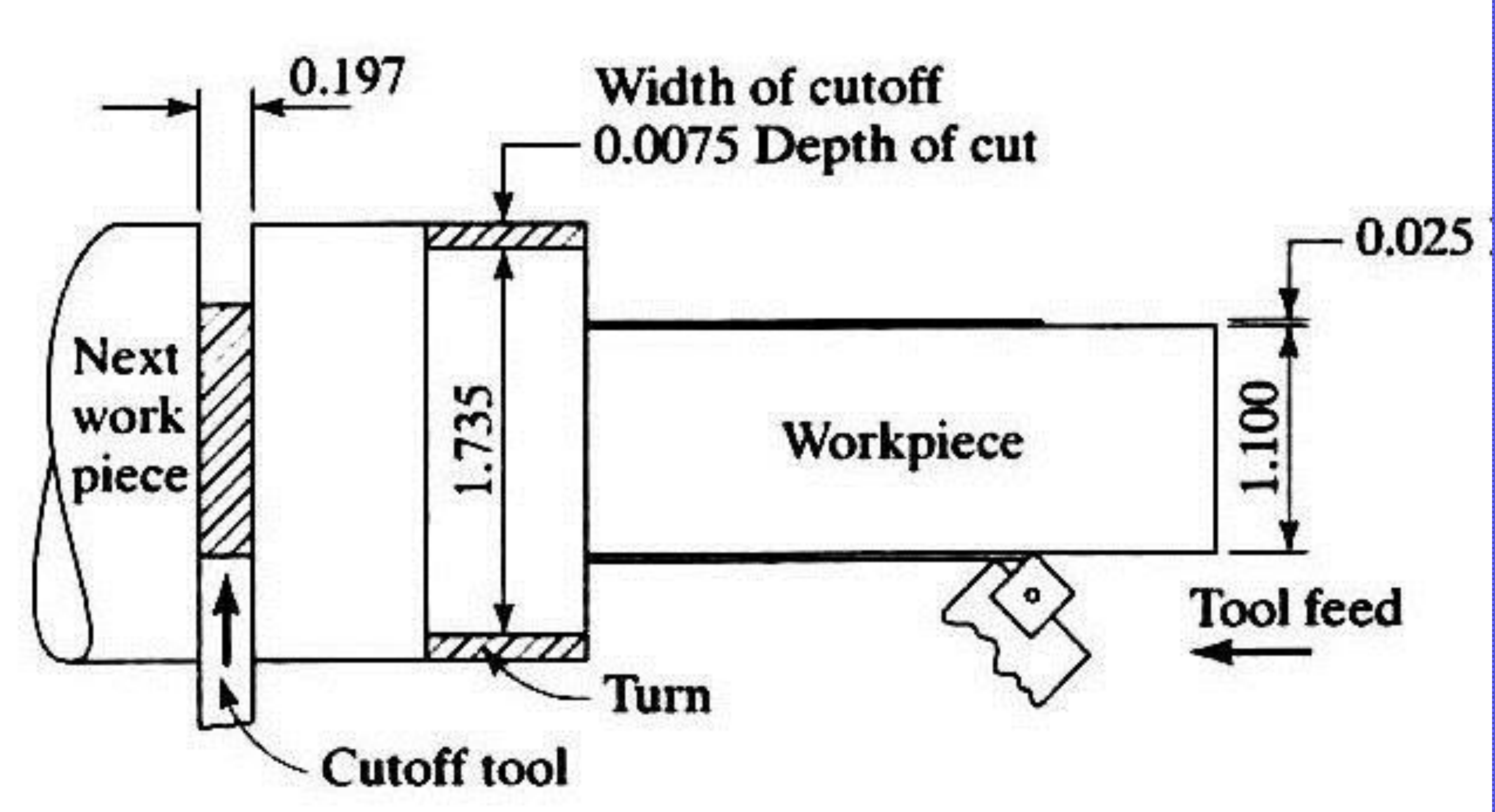
Elem	Dim	Depth of Cut	L_d	L_s	L	D	V fpm	f (ipr)	t_m min
Rough turn	1.45	0.15	16.5	1/32	16.5	1.75	350	.015	1.44

Second Rough Turn



Elem	Dim	Depth of Cut	L_d	L_s	L	D	V fpm	f (ipr)	t_m min
Rough turn	1.15	0.15	16.5	1/32	16.5	1.45	350	.015	1.19

Remaining Elements



Cycle Times for Remaining Elems

Elem	Dim	Depth of Cut	L_d	L_s	L	D	V fpm	F (ipr)	$t_{m,}$ min
Finish turn	1.10	0.025	16.5	1/32	16.53	1.15	350	007	2.03
Elem 5 Turn	1.73	.0075	0.5	1/32	0.53	1.75	350	007	0.10
Cutoff	1.75		.875	1/32	0.906	1.75	350	015	0.08

Operation 10 Totals

Subtotal of machining times		5.01
Total cycle time for handling and machining		6.36

D. Entry values for operation sheet, operation 10	
Setup hr	3.2
Hr/100 units	10.600

Calculating Length of Cut

- For Rotating Cutters
- Length of Travel at Feed Rate

$$L = L_s + L_a + L_d + L_{ot}$$

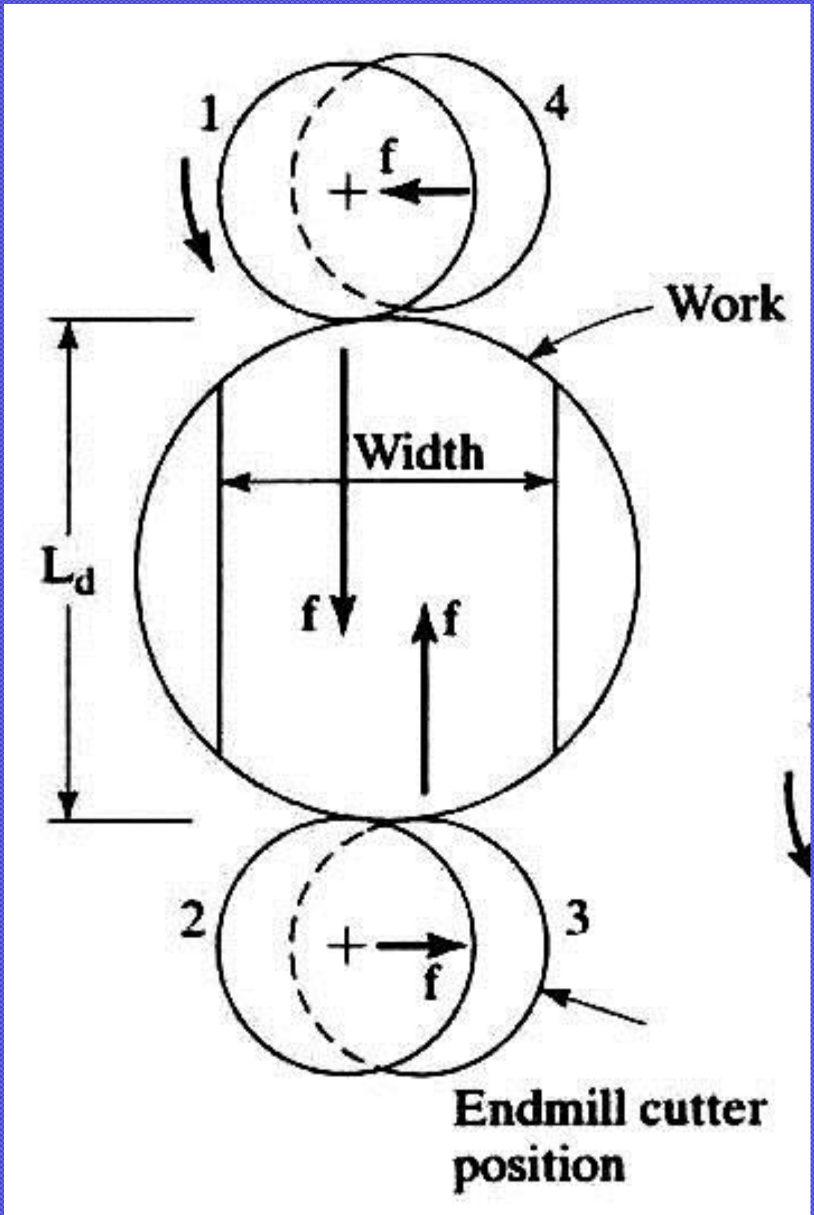
Eq 7.14

- Safety Length
  - For Stock and Mounting Variations

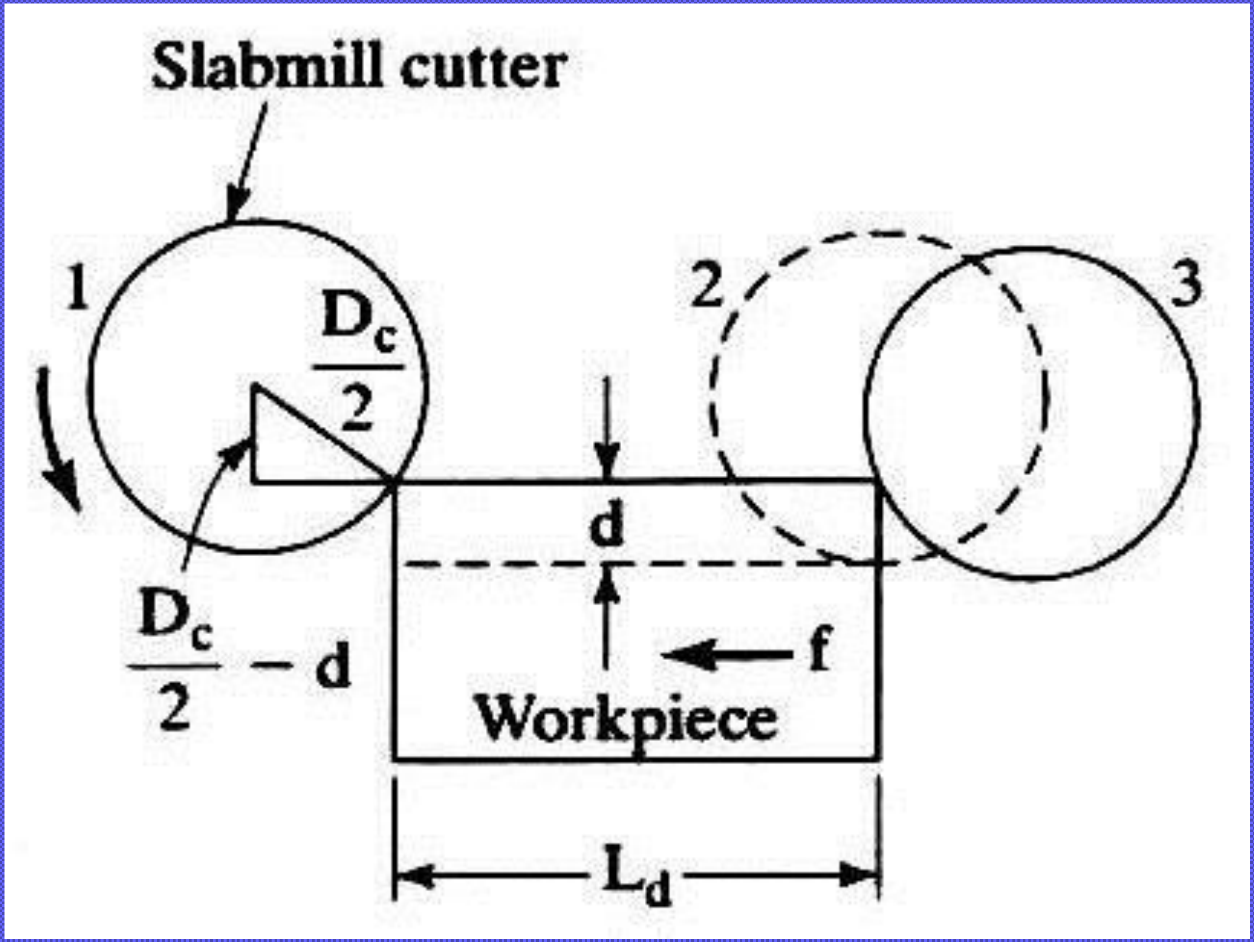
Other Length Factors

- Approach/Over Travel
  - –Gets Cutter Fully Into & Out of Work
  - –Many Times = Cutter Radius but…
  - –Over Travel May Not Be Required
- Design Length
  - –Actual Length Making Cut
  - –Include All Passes and Lateral Moves

End Mill Length of Cut



Peripheral Cutting Length



Approach Length Differs

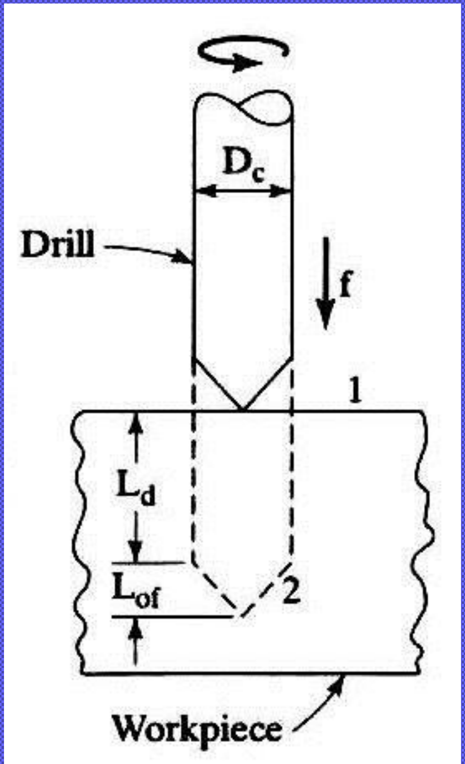
- Peripheral Milling Need to Consider:
  - –Cutter Diameter
  - –Depth of Cut

$$L_a = \sqrt{\left(\frac{D_c}{2}\right)^2 - \left(\frac{D_c}{2} - d\right)^2} = \sqrt{d\left(D_c - d\right)}$$

Eq 7.15

Drilling

- Approach Includes Point Angle



$$L_{ot} = \frac{D_c}{2\tan 59} = 0.3D_c$$

Eq 7.16

Operation 20

- Set Up (from Table 7.4)

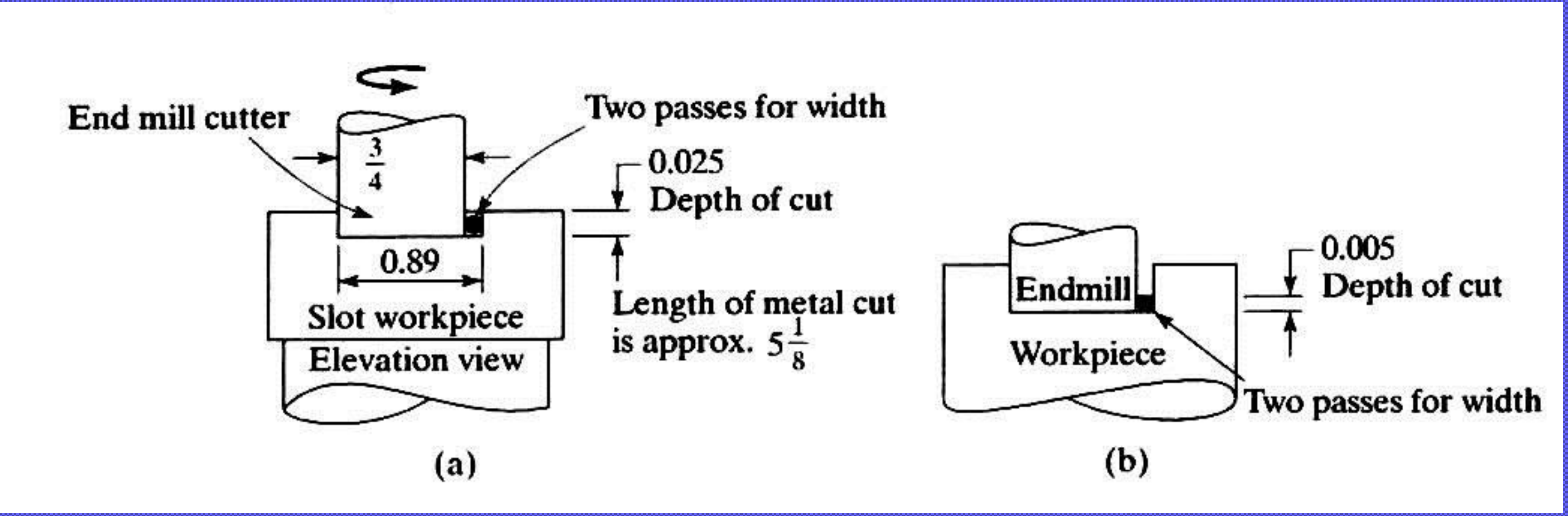
A. Setup elements	Hr
Punch in and out, study drawing	0.2
Slot-cut milling collet	1.6
Setup total, operation 20	1.8

Handling

- From Table 7.5

B. Handling and other equipment time elements	Min
Start and stop machine	0.08
Air clean part	0.06
10 ≤ lb < 15 lb load into collet	0.25
Open and close air vise	0.06
Change speeds and feeds, 2 x	0.08
Subtotal of handling	0.53

End Milling


End mill cutter
3/4
Two passes for width
0.025
Depth of cut
0.89
Slot workpiece
Elevation view
Length of metal cut
is approx. 5 1/8
(a)
Endmill
Workpiece
0.005
Depth of cut
Two passes for width
(b)

End Milling Times

Element	L_d	Milling Cutter	V fpm	f_t (ipr)	t_m, min
Rough mill slot	6.81	0.75 in. end mill, 4 flute	85	0.002	1.97
Finish mill slot	6.81	0.75 in. end mill, 4 flute	95	0.0015	2.34

Operation 20 Totals

Subtotal of machining times		4.31
Total cycle time for handling and machining, min		4.84

D. Entry values for operation sheet, operation 20	
Setup hr	1.8
Hr/100 units	8.067

Operation 30

- Set Up (from Table 7.4)

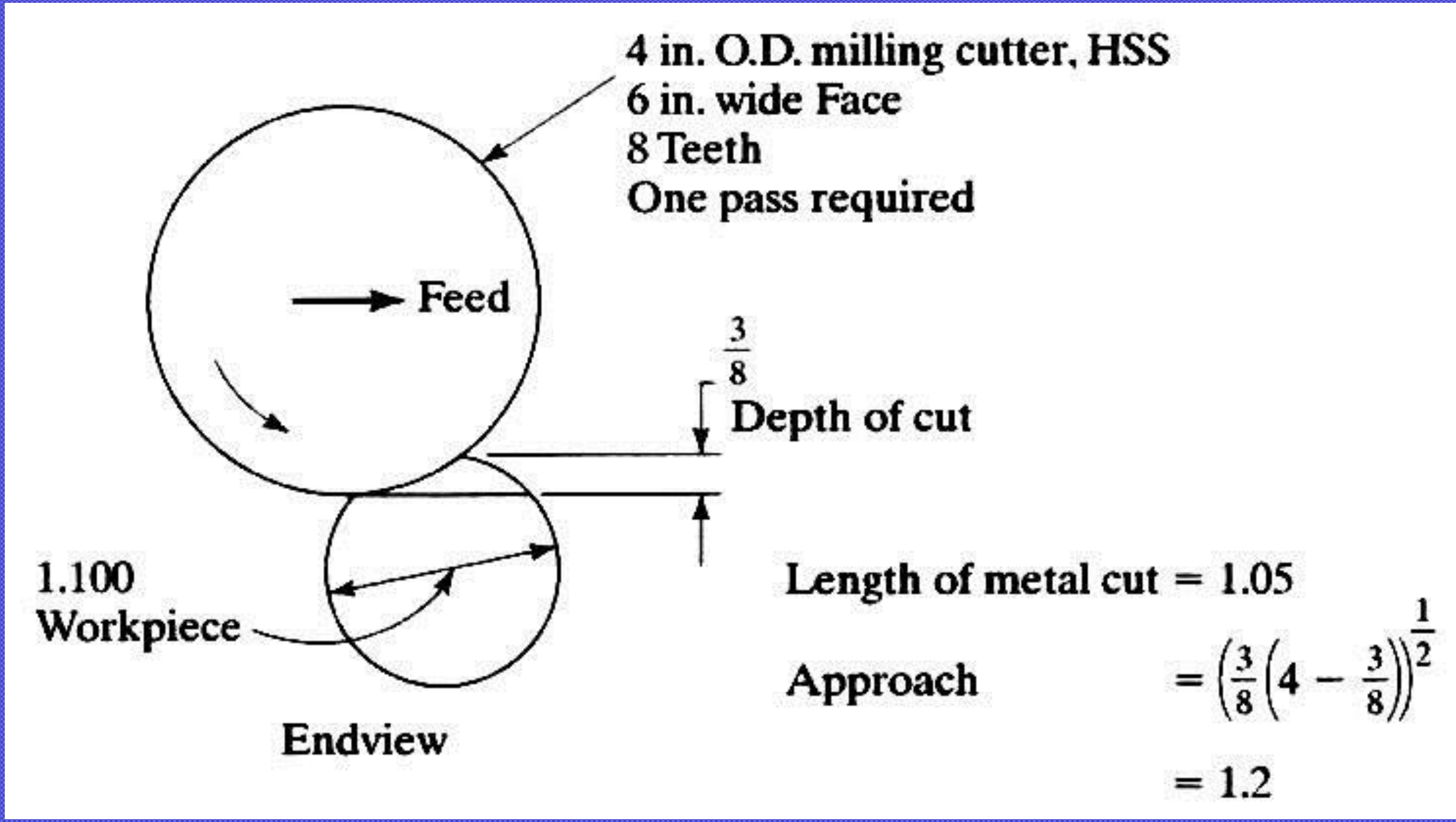
A. Setup elements	**Hr**
Punch in and out, study drawing	0.2
Special vise	1.1
Setup total, operation 30	1.3

Handling

- From Table 7.5

B. Handling and other equipment time elements	**Min**
Start and stop machine	0.08
Air clean part	0.06
10 ≤ lb < 15 lb load into collet fixture	0.25
Open and close air vise	0.06
Subtotal of handling and other equipment	0.45

Peripheral Milling



Length of Cut

- Peripheral Milling
  - –Use Equation 7.15 for Approach and OT

    Cutter 4” Dia, Depth of Cut = 3/8”

$$\sqrt{0.375(4-0.375)} = 1.2$$

- L_d = 1.05, L_a = L_{ot} = 1.2 (L_s in Rounding of L_a)
- L = 1.05 + 2(1.2) = 3.45

Peripheral Milling Times

Element	L_d	Milling Cutter	V fpm	$f_t d$ ($i_t$pr)	t_m
Mill flat on end	3.45	4 in. O.D., 8 tooth	210	0.005	0.43

Operation 30 Totals

Subtotal of machining times		0.43
Total cycle time for handling and machining, min		0.88

D. Entry values for operation sheet, operation 30	
Setup hr	1.3
Hr/100 units	1.467

Operation 40

- Set Up (from Table 7.4)

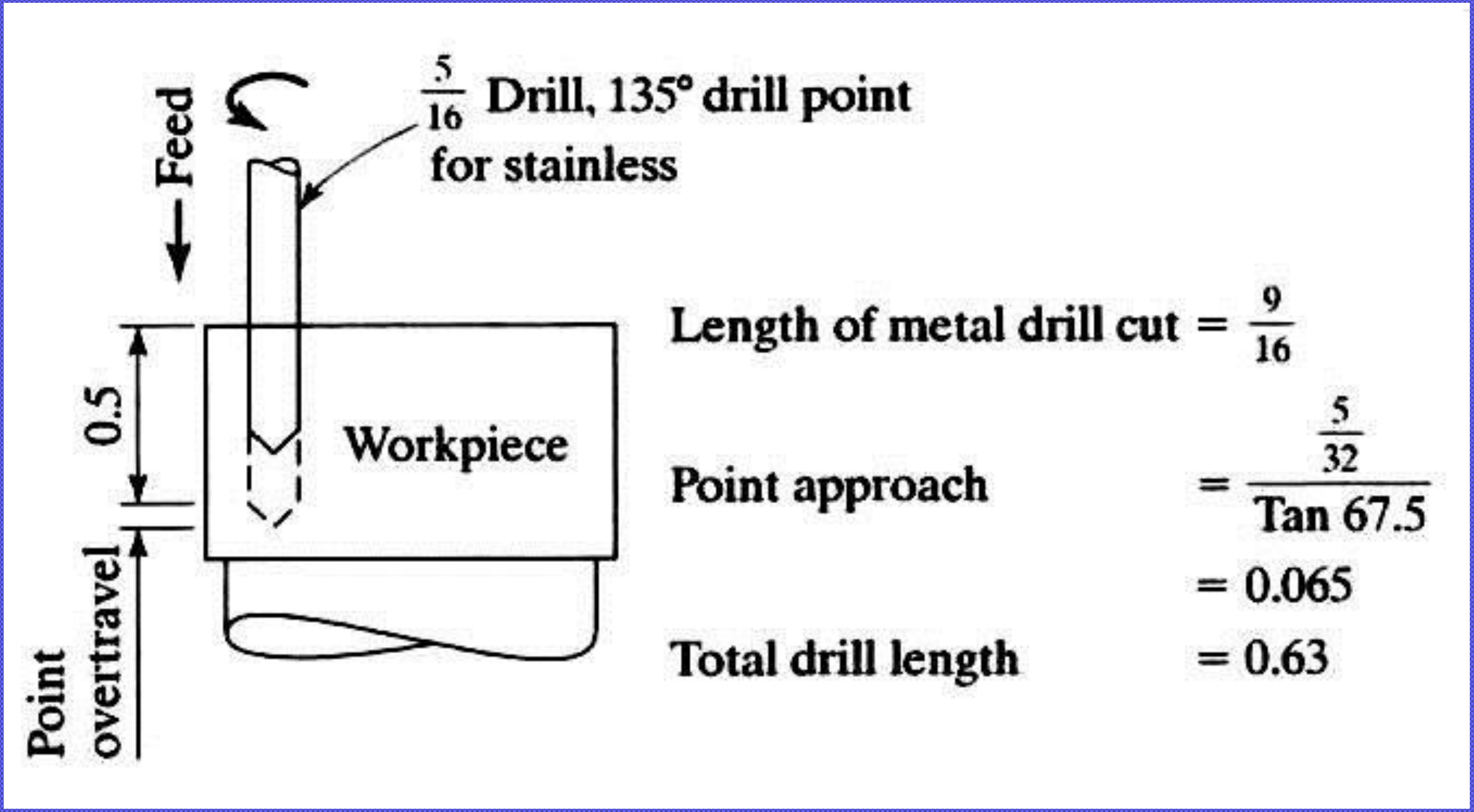
A. Setup elements	Hr
Punch in and out, study drawing	0.2
First turret station for drill	0.75
Second turret station for tap	0.07
Collet for holding	0.1
Setup total, operation 40	1.12

Handling

- From Table 7.5

B. Handling and other equipment time elements	Min
Start and stop machine	0.08
Air clean part	0.06
$10 \leq$ lb < 15 lb load/unload part into collet	0.22
Open and close air collet clamping	0.05
Index turret, 2 x for drilling and tapping	0.06
Raise tool, move to new locations, 8 x	<u>0.48</u>
Subtotal of handling and other equipment	0.95

Drilling



5/16 Drill, 135° drill point
for stainless
Feed
0.5
Point
overtravel
Workpiece
Length of metal drill cut = 9/16
Point approach = (5/32)/(Tan 67.5)
= 0.065
Total drill length = 0.63

Drilling Time

Tool	L_d	f_{dt}	Lf_{dt}	No. holes	t_m, min
Drill, 5/16	0.63	0.61	0.38	4	1.52
Tap, 3/8 – 16	0.5	0.33	0.17	4	0.66

Operation 40 Totals

Subtotal of machining times		2.18
Total cycle time for handling and machining, min		3.13

D. Entry values for operation sheet, operation 40	
Setup hr	1.12
Hr/100 units	5.217

Post All of the Times

Op. no.	**Setup hr**	**Cycle hr/100 units**	**Lot Hr** (Qty = 200)
10	3.2	10.600	24.4
20	1.8	8.067	17.9
30	1.3	1.467	2.9
40	1.12	5.217	10.4

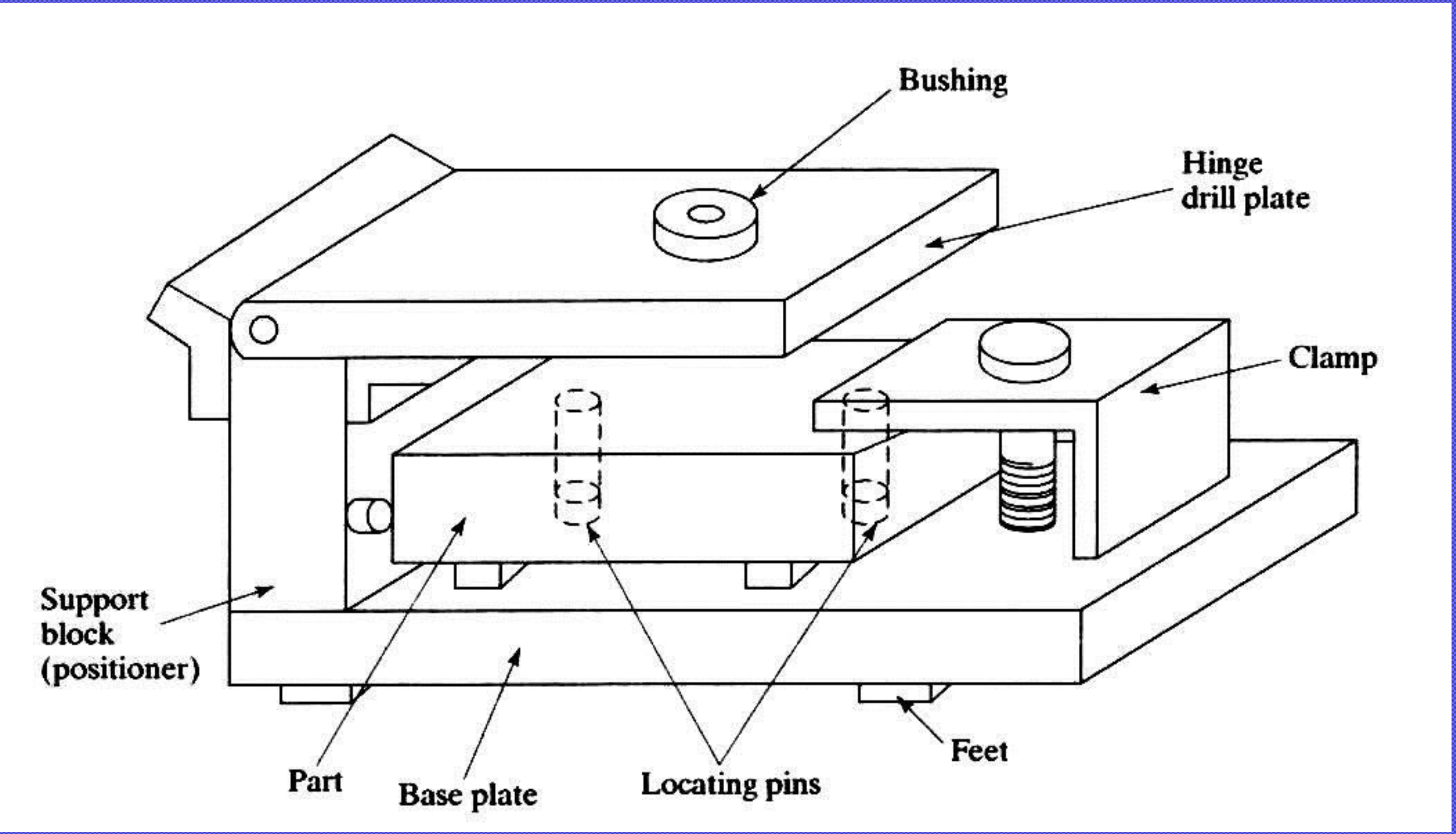
Tool Cost

- Tools Facilitate Manufacturing
- Tool Cost Is Part of Operation Cost
- Tools – Permanent, One-Time Cost
  - –Nonrecurring, Initial Fixed Cost
- Tools Require Engineering Design
- Tools Can Be a Large Cost

Tool Cost Estimating

- Simple Methods
  - –Standard Time Data
  - –Use Tables
  - –Broad, General Categories
- One Time Cost
  - –Estimate Less Critical
  - –Usually Hours Is the Increment

Drill Jig Example



Drill Jig Cost

Description of tool elements	Hr
Angular base plate, C-angle	7.0
Guide bushing	2.0
Hinge plate	12.0
Clamp with screw	7.5
Feet, 3	7.5
Pin locators, 5	8.8
Total	44.8
Productive hour cost for tool making	$75
Cost of tool, 44.8 x 75	$3360
Material cost, $25/lb	200
Total cost of tool	$3560

What to Do with Tool Costs

- Add to Overhead (NOT Recommended)
- Amortize Over Production

$$C_{ot} = \frac{C_{nif}}{N}$$

Eq 7.18

- *N* Is Critical
  - –Too Small *N*, Tooling Cost Too High
  - –Too Large *N*, Tooling May Not Be Paid For

Tooling vs. No Tooling

- Compare Manufacturing Cost
  - –Using Tooling (Saves Labor)
  - –Without Tooling (Additional Labor)

$$C_{nif} = \frac{Na(1+p) - SU}{I + T + D + M}$$

Eq 7.19

Calculate the Operation Cost

- Batch Manufacturing Situation
- Determine Hours for the Lot

$$\text{lot hours} = SU_b + N \times H_b \qquad \text{Eq 7.20}$$

- Find the Batch (Lot) Cost

$$C_{bo} = \text{lot hours} \times PHC_i \qquad \text{Eq 7.21}$$

Total Product Manufacturing Cost

- Cost for All Operations

$$C_{tbo} = \sum_{i}^{n} \text{lot hours}_i \times PHC_i$$

- Include Material and Tooling Costs

$$C_{bu} = \sum C_{bo} / N + C_{dm} + \sum C_{ot} / N$$

Eq 7.22

Cost for Pinion Example

Op. no.	Lot hr	PHC	Lot cost	Unit cost
10	24.4	39.16	$955	$4.78
20	17.9	90.98	$1631	$8.16
30	2.9	90.98	$267	$1.34
40	10.4	39.16	$409	$2.04
	Total Lot Cost		$3262	
	Unit Production Cost			$16.32
Total Unit Cost (incl. $21.43 Matl)				$37.66

Flow Line Manufacturing

- Mass Production, Assembly Lines
- All Operations Interdependent
- Times Determined from Station Requiring the Longest Time
- Imbalance Leads to Idle Time for Other Stations

Flow Line Set Up Time

- Find Maximum Station Set Up Time

$$SU_f = \max\{SU_i\}$$

- Total Cost for Line Set Up

$$\text{Set Up Cost} = \sum_{i}^{n} PHC_i \times SU_f, \; i = 1, 2, \cdots, n$$

Eq 7.23

Flow Line Cycle Time

- Find Maximum Station Cycle Time

$$H_f = \max\{H_i\}$$

- Total Cost for Line Cycle Time

$$\text{CycleCost} = N \sum_{i}^{n} PHC_i \times H_f, \quad i = 1, 2, \cdots, n$$

Eq 7.24

Total Product Time (Flow Line)

- Determine Lot Hours

$$\text{lot hours} = nSU_f + nNH_f \qquad \text{Eq 7.25}$$

- If nSU_f is Very Small Compared to nNH_f
  - –Set Up Cost Can Be Ignored
  - –Covered in Overhead

Total Product Cost (Flow Line)

- Total Labor Cost

$$C_f = \sum_{i}^{n} PHC_i \times SU_f + N \sum_{i}^{n} PHC_i \times H_f$$

Eq 7.26

- Total Product Cost

$$C_{fu} = C_f / N + C_{dm} + \sum C_{ot} / N$$

Eq 7.27

Summary

- Determined Costs for Manuf. Operations
- Found Direct Labor Times
  - Set Up and Cycle Times
  - Machining Time
- Studied a Metal Machining Example
- Added Tooling Costs
- Briefly Looked at Flow Line Costs