Economics and Product Design Considerations

1. Machinability
2. Tolerance and Surface Finish
3. Selection of Cutting Conditions
4. Product Design Considerations

1. Machinability
- Machinability — A measure of the relative ease of a machining operation usually on a work material and type of machining operation, tooling, and cutting conditions.
  - Longer tool life means better machinability
  - Greater forces and power mean lower machinability
  - Better surface finish means better machinability
  - Easier chip disposal means better machinability
  - Higher MRR means better machinability
- Mechanical properties and Machinability
  - High hardness of work materials means abrasive wear resistance
  - High strength of work materials means cutting forces, specific energy, and cutting temperature increase
  - High ductility of work materials means tearing of metal as chip is formed, causing chip disposal problems and poor surface finish

2. Tolerances & Surface Finish
- Tolerances
  - Machining provides high accuracy relative to most other processes
  - Closer tolerances usually mean higher costs
- Surface roughness in machining is determined by:
  - Work material factors
  - Geometric factors of the operation
  - Vibration and machine tool factors
- Work Material Factors
  - Built-up edge effects
  - Damage to surface caused by chip
  - Tearing of surface for ductile materials
  - Cracks in surface for brittle materials
  - Friction between tool flank and new surface

Tolerance and Surface finish
- Geometric factor
  - Types of Operations
    - Cutting tool geometry
      - Surface roughness, $R_s = \frac{f}{2\pi NR}$
        - where $NR$: nose radius
        - $f$: cutting speed
        - $R_s$: surface roughness
    - Other expressions of roughness
      - Nose Radius, Feed and End Cutting Edge Angle

Shape
- Shape
  - Rotational parts — turning and boring
  - Internal rotational features — drilling
  - Non-rotational parts — milling
  - Dependency on the geometry of a tool
    - Generating — Multi-axis milling machine
    - Forming — form turning, drilling and broaching
    - Generating/Forming (threading)
### Typical Tolerance Surface Finish

<table>
<thead>
<tr>
<th>Machining Operations</th>
<th>Tolerance (Typical)</th>
<th>Surface Finish (Typical best)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning</td>
<td>D&lt;12mm</td>
<td>±0.025</td>
</tr>
<tr>
<td></td>
<td>D&gt;12mm</td>
<td>±0.075</td>
</tr>
<tr>
<td>Drilling</td>
<td>D&lt;2.5mm</td>
<td>±0.025</td>
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<tr>
<td></td>
<td>2.5mm&lt;D&lt;16mm</td>
<td>±0.075</td>
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<tr>
<td></td>
<td>D&gt;16mm</td>
<td>±0.075</td>
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<tr>
<td>Sawing</td>
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</tr>
<tr>
<td>Planing</td>
<td>D&gt;12mm</td>
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<tr>
<td></td>
<td>D&gt;25mm</td>
<td>±0.025</td>
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<tr>
<td>Slotting</td>
<td>D&gt;25mm</td>
<td>±0.05</td>
</tr>
<tr>
<td>Shaping</td>
<td>D&gt;25mm</td>
<td>±0.05</td>
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<tr>
<td>Broaching</td>
<td>D&gt;25mm</td>
<td>±0.05</td>
</tr>
<tr>
<td></td>
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<td>±0.075</td>
</tr>
<tr>
<td></td>
<td>D&gt;25mm</td>
<td>±0.075</td>
</tr>
<tr>
<td>Peripheral Milling</td>
<td>D&gt;25mm</td>
<td>±0.05</td>
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<tr>
<td></td>
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<td>±0.075</td>
</tr>
<tr>
<td></td>
<td>D&gt;25mm</td>
<td>±0.075</td>
</tr>
<tr>
<td>D&lt;12mm</td>
<td>±0.075</td>
<td>0.4µm±0.075</td>
</tr>
<tr>
<td>Reaming</td>
<td>D&lt;2.5mm</td>
<td>±0.025</td>
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<tr>
<td></td>
<td>2.5mm&lt;D&lt;12mm</td>
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</tr>
</tbody>
</table>

### Chatter (Vibration)
- Vibration and Chatter
  - Related to machine tool, tooling, and setup:
    - Chatter (vibration) in machine tool or cutting tool
    - Deflections of fixtures
    - Backlash in feed mechanism
  - Without chatter, surface roughness is determined by geometric and work material factors
- How to avoid Chatter
  - Add stiffness and/or damping to setup
  - Operate at speeds that avoid natural frequency of machine tool system
  - Reduce feeds and depths to reduce forces
  - Change cutter design to reduce forces
  - Use a cutting fluid

### 3. Selection of Cutting Conditions
- One of the tasks in process planning
- For each operation, decisions on machine tool, cutting tool(s), and cutting conditions based on workpart machinability, part geometry, surface finish, and so forth
- Cutting Tool Manufacturer’s Recommendation
- Cutting conditions: speed, feed, depth of cut, and cutting fluid
  - Depth of cut predetermined by workpiece geometry and operation sequence.
    - In roughing, high depth to maximize material removal rate, but limited by horsepower, machine tool and rigidity, and strength of cutting tool.
    - In finishing, depth to achieve final part dimensions

### Selecting Feed and Speed
- Feed: In general: feed first, speed second
  - Tooling – Harder tool materials require lower feeds
  - Roughing or finishing - Roughing means high feeds, finishing means low feeds
  - Constraints on feed in roughing: cutting forces, setup rigidity, and sometimes horsepower
  - Surface finish requirements in finishing – Select feed to produce desired finish
- Cutting Speed
  - Select speed to achieve a balance between high metal removal rate and suitably long tool life
  - Mathematical formulas are available to determine optimal speed
  - Two alternative objectives:
    1. Maximum production rate
    2. Minimum unit cost

### Maximum Production Rate
- Maximizing production rate = minimizing cutting time per unit
- In turning, total production cycle time for one part consists of:
  - Part handling time per part = $T_h$
  - Machining time per part = $T_m$
  - Tool change time per part = $T_{tc}$, where $n_p$ = number of pieces cut in one tool life where
    $$n_p = \frac{T}{T_m} = \frac{t}{dE/LV^m}$$
    and, from Taylor’s model, tool life is
    $$T = C'V_w^{1/m}$$
Example

Workpart: L=300mm and D=80mm
Taylor’s Eq. for a HSS tool: n=0.13 and C=75(m/min)
Operator and machine cost=$0.01/hr
Tooling cost/edge=$0.01
2min to load and unload and 3.5min to change tools
(a) Cutting speed for max. production rate
(b) Tool life in min. for max. production rate
(c) Cycle time and cost per unit of product for max. production rate

\[ v = \frac{C}{n + \frac{D}{v}} \]

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Minimum Cost Per Part

- Cost of part handling: \( C_T a \)
- Cost of machine time: \( C_T a \)
- Cost of tool change: \( C \frac{T}{p} \)

- Tooling cost: \( C_i = \frac{p}{n_i} \) for disposable inserts
  \( C_i = \frac{p}{n_i} + T_{t} \frac{C}{C_t} \) for regrindable inserts

\[ C = C_T a + C_T a + C \frac{T}{p} \]

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Comments

- As C and n increase in Taylor’s equation, optimum cutting speed should be reduced
  - Cemented carbides & ceramic tools at higher speeds.
  - \( V_{max} \) is always greater than \( V_{min} \).
    - Reason: \( C/R_0 \) term in unit cost equation pushes optimum speed to left in the plot of \( C/T \) vs. \( v \).

- Cutting speed should be reduced as tool change time \( T_{t} \) and/or tooling cost \( C_t \) increase,
  - Tools should not be changed too often if either tool cost or tool change time is high.
  - An advantage of disposable inserts over regrindable tools due to the lower tool change time.

Product Design Guidelines I

- Design parts to minimize machining
  - By using net shape (precision casting, closed die forging, or plastic molding) or near net shape processes (impression die forging)
- Essential Reasons for machining
  - Close tolerances
  - Good surface finish
  - Flexibility
  - Special features such as threads, precision holes, cylindrical sections with high degree of roundness
- Specify Tolerances to satisfy functional requirements and process capabilities (unnecessary cost from additional processing, finishing, inspection, sortation, rework, and scrap)
- Specify surface finish to meet functional and/or aesthetic requirements (add processing cost by requiring additional operations such as grinding or tapping)

Product Design Guidelines II

- Avoid features such as sharp corners, edges, and points
  - They are difficult to machine
  - Sharp cutting tools tend to break and create burrs
- Machined parts from standard stock sizes
- Machining with standard cutting tools
  - Avoid special form tools
  - Minimize the number of individual cutting tools used
- Select materials with good machinability
  - Materials with low machinability take longer and cost more.
  - Minimize the number of setups