2.810 Manufacturing Processes and Systems
Practice Quiz #1 Solutions

Open book, open notes, computers with internet off
Time: 80 minutes

Problems:

1. How were these parts made? (XX points)
2. Process plan for bike chain puller body (XX points)
   + Extra credit question (XX points)
3. Injection molding (XX points)
4. Micro turning lathe (XX points)
5. Injection molding redesign (XX points)
1. How were these parts made? (XX points)

Examine the electrical connector that you were given. For each of the four part types, identify the materials, the primary processes, and the secondary processes (if any) used to manufacture it. Be sure to list the reasons why you decided upon the materials and manufacturing processes that you listed. You may draw on the picture below to point out features or details that you are referring to.

![Image of electrical connector parts]

<table>
<thead>
<tr>
<th>Part</th>
<th>Material(s)</th>
<th>Reasons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Zinc</td>
<td>Appearance (soft alloy), weight (heavier than Aluminum), good material to die cast</td>
</tr>
<tr>
<td>2</td>
<td>Zinc</td>
<td>Same as above</td>
</tr>
<tr>
<td>3</td>
<td>Steel</td>
<td>Inexpensive, stamped part</td>
</tr>
<tr>
<td>4</td>
<td>Steel</td>
<td>Typical material for screws; inexpensive</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Part</th>
<th>Process(es)</th>
<th>Reasons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Die cast (some post-process machining)</td>
<td>High volume part, cheap, no undercuts, appears to be soft and easy to die cast</td>
</tr>
<tr>
<td>2</td>
<td>Die cast</td>
<td>Parting line is clearly visible</td>
</tr>
<tr>
<td>3</td>
<td>Stamped and formed; galvanized (Zn plated)</td>
<td>Edge finish; constant thickness</td>
</tr>
<tr>
<td>4</td>
<td>Threads rolled in wire stock; headed and slot made by forming</td>
<td>Typical screw production process; slot turning</td>
</tr>
</tbody>
</table>
2. Process plan for bike chain puller body (XX points)

The bike chain puller “tool body” shown on the following page can be made from hexagonal steel stock by machining. Assume it has already been cut and machined to length. Please write down the process steps to make the features listed below and called out on the drawing:

1. three lands of different widths,
2. radiused slot,
3. hole in base.

For each feature, identify the machines, tools, and fixtures needed for each operation, and the sequence of operations required. For each feature that you machine, sketch a simple schematic showing your set-up, namely the positions of the part, fixture, and tool. Your sketch should also show the orientation of the part. Point out any part of a feature that is particularly difficult to make. Use the blank process plan sheet that is provided.

You do not need to estimate times. You only need to write a process plan.

All dimensions are in inches. Unless otherwise indicated, tolerances are ±0.005 inches. Please state all assumptions clearly.

Extra credit (XX points)

a) Write down the process steps to make the following features:
   4. horizontal threaded hole,
   5. radiused profile on ridges between lands.

b) Estimate the time to machine feature 1.
<table>
<thead>
<tr>
<th>#</th>
<th>Machine</th>
<th>Tool</th>
<th>Operation</th>
<th>Fixture</th>
<th>Sketch</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>vertical mill</td>
<td>1/2&quot; end mill</td>
<td>remove mtl above ridges (0.20 deep) vise</td>
<td><img src="image1" alt="Sketch" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td>vertical mill</td>
<td>1/4&quot; end mill</td>
<td>remove 0.25&quot; land (0.92 - 0.67) width vise (0.27 deep)</td>
<td><img src="image2" alt="Sketch" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td>vertical mill</td>
<td>0.10&quot; end mill</td>
<td>remove 0.10 land (0.32 - 0.22) width</td>
<td><img src="image3" alt="Sketch" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>or remove 0.10 land (0.57 - 0.39) width</td>
<td><img src="image4" alt="Sketch" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>or change tool to 0.15 - 0.20</td>
<td><img src="image5" alt="Sketch" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bench</td>
<td>deburr, inspect, measure</td>
<td><img src="image6" alt="Sketch" /></td>
</tr>
<tr>
<td>2</td>
<td>vertical mill</td>
<td>0.187&quot; end mill</td>
<td>remove mtl 0.310 in</td>
<td><img src="image7" alt="Sketch" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>or bench 0.15&quot; or smaller with circular interpolator</td>
<td><img src="image8" alt="Sketch" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>deburr, inspect, measure</td>
<td><img src="image9" alt="Sketch" /></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>vert mill</td>
<td>0.15&quot; end mill</td>
<td>circular interpolate for flat bottom hole</td>
<td><img src="image10" alt="Sketch" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>smaller than 0.1875</td>
<td><img src="image11" alt="Sketch" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>no resmach necessary</td>
<td><img src="image12" alt="Sketch" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>depth 0.20</td>
<td><img src="image13" alt="Sketch" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>bench</td>
<td>deburr, inspect, measure</td>
<td><img src="image14" alt="Sketch" /></td>
</tr>
<tr>
<td>4</td>
<td>vertical mill</td>
<td>.031 drill bit</td>
<td>drill hole vise</td>
<td><img src="image15" alt="Sketch" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td>drill press</td>
<td>top</td>
<td>+1</td>
<td><img src="image16" alt="Sketch" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>top lock</td>
<td>+1</td>
<td>0.3125 - 24 UNF vise</td>
<td><img src="image17" alt="Sketch" /></td>
</tr>
<tr>
<td>5</td>
<td>vert mill</td>
<td>drill-thread machine profile</td>
<td></td>
<td><img src="image18" alt="Sketch" /></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>+1</td>
<td><img src="image19" alt="Sketch" /></td>
<td></td>
</tr>
</tbody>
</table>
Feature 1. Use a flat end mill to clear out the required material, possibly using larger endmills where possible (multi-tool strategy). Could be done on a manual or CNC three-axis mill.

Another option: use peripheral mills to machine away material. Again, multiple widths could be used, but the smallest would need to be 0.100".
Feature 2. Fixture the work piece as shown and use a 3/16” flat end mill to create the slot. Could be done in a manual or CNC mill.

Feature 3. Use a 3/16” center-cutting flat end mill to create the hole since it needs to have a square bottom. You could also spot drill and drill the hole first to remove most of the material, but would need to finish with the flat end mill. Reaming is likely not required to hold a tolerance of ±0.002”, particularly if using an end mill.

Feature 4. Use a letter ‘I’ drill (0.272” diameter) to create the hole, after spot drilling. Then, use a 5/16–24 tap to create the threads. The hole could be cut on a drill press or mill, and the tapping can be done manually.
**Feature 5.** This is a tricky feature to create because it is more than a half-circle. To cut this feature, you need to use a T-slot cutter (so that the shaft is much smaller than the cutting head) and approach through either the slot (#2) or the threaded hole (#4, do this before tapping so you don’t damage the threads). Because this feature is an odd diameter, you need to use circular interpolation to create the surface, limiting you to a CNC mill (a rotary table on a manual mill would likely not hold the required tolerances).

Things to consider if mass-producing this part:
- Create a custom form tool for feature #1
- Create custom tooling (correct diameter) for #5
- Set up a CNC mill to both drill and tap #4
- Consider having a near-net shape component (i.e. forging) made, then finish machine the critical features. This would eliminate all of the rough machining and thus reduce overall machining time. Consider the time and material savings versus the cost of tooling for forging.
3. Injection molding (XX points)

Look at this tape cassette case carefully. You only need to consider the top cover, shown in pictures 1 and 3. Estimate some basic parameters about the nature of the manufacturing process used to make this part.

![Picture 1. Top cover.](image1)

![Picture 2. Cassette case with top open.](image2)

![Picture 3. Top cover.](image3)

a) Estimate the clamping force (in pounds force), if the dimensions L x W x H are 3.94 in x 2.69 in x 0.75 in.

The clamping force depends on the projected area of the part and the maximum pressure in the mold during filling. The projected area of this part is L x W (since this is a rough estimate, we can neglect the additional projected area of the runners):

\[ A = 3.94 \text{ in} \times 2.69 \text{ in} = 10.60 \text{ in}^2 \]
The maximum pressure during mold filling depends on the material. This case is made from polystyrene, so using the values provided by Boothroyd (Table 8.5), the injection pressure should be:

\[ P = 965 \text{ bars} = 14,000 \text{ psi} \]

Then we can find the required clamping force:

\[ F [\text{lbs}] = P [\text{psi}] \times A [\text{in}^2] \]

\[ F = 14,000 \text{ psi} \times 10.60 \text{ in}^2 = 148,400 \text{ lbs} = 74.2 \text{ tons} \]

Unit conversions:
1 bar = 14.5 psi
1 ton = 2000 lbs

b) Estimate the cooling time (in seconds), if the thickness of the plastic is 1/12 in.

You could use two ways to estimate the cooling time. The first approach is to use the formula from lecture for a rough estimate:

\[ t_{cool} = \frac{\left(\frac{h}{2}\right)^2}{\alpha} \]

where

\( h \) = wall thickness = 1/12 in = 2.1 mm
\( \alpha \) = thermal diffusivity of polymers = 10\(^{-3}\) cm\(^2\)/s = 0.1 mm\(^2\)/s

\[ t_{cool} = \frac{(2.1/2)^2}{0.1} = \frac{1.1025}{0.1} = 11 \text{ sec} \]

The second approach is by using Equation 8.5 from Boothroyd for the cooling time and plugging in values from Table 8.5 for polystyrene:

\[ t_{cool} = \frac{h_{max}^2}{\pi^2 \alpha} \ln \frac{4(T_i - T_m)}{\pi(T_x - T_m)} \]

where

\( h_{max} \) = maximum wall thickness = 2.1 mm
\( \alpha \) = thermal diffusivity of the polymer = 0.09 mm\(^2\)/s
\( T_i \) = polymer injection temperature = 218°C
\( T_m \) = mold temperature = 27°C
\( T_x \) = part ejection temperature = 77°C

\[ t_{cool} = \frac{2.1^2}{\pi^2 0.09} \ln \frac{4(218 - 27)}{\pi(77 - 27)} = 4.965 \ln \frac{764}{157} = 7.9 \text{ sec} \]
c) Make a sketch of the tooling needed to make this part. Point out the gate location and the special tooling features required, if any.
4. Micro turning lathe (XX pts)

Consider the micro-turning lathe shown above. This lathe is capable of turning an \( L = 1 \) mm long aluminum needle with a diameter of \( d = 65 \) µm using a polycrystalline diamond, PCD, tool. The spindle speed was \( n = 10,000 \) rev-min\(^{-1}\) resulting in a cutting speed of \( v_c = 2 \) m/min while the feed was \( f = 0.12 \) µm and the depth of cut \( a_p = 2 \) µm. The electrical power required for this machine is 65 W.

a) Estimate the material removal rate in cm\(^3\)/sec.
b) Estimate the electrical energy used per unit volume of material removed (in kJ/cm³) and unit mass removed (in J/kg).

Also note:

\[
\frac{8 \times 10^{-9} \text{ cm}^3}{\text{sec}} \times \frac{2.7 \text{ g}}{\text{cm}^3} \times \frac{3600 \text{ sec}}{1 \text{ hr}} = 777.6 \times 10^9 \text{ g/hr} = 8 \times 10^9 \text{ kg/hr}
\]

Machine uses 65 Watts

\[
\frac{P}{m} = \frac{E}{m} = \frac{65 \frac{J}{s}}{8 \times 10^{-9} \frac{\text{cm}^3}{s}} = \frac{8 \times 10^9 \text{ J}}{2.7 \text{ g}} = 3 \times 10^9 \frac{J}{\text{g}} = 3 \text{ TJ/kg}
\]

Note #1: See attached figure for comparison with conventional MFG processes.

Note #2: If you estimate power for cutting (spindle power)

Using: \( U_s = 0.4 \text{ to } 1 \frac{\text{W}}{\text{mm}^3} \) (Say \( U_s = 0.7 \frac{\text{W}}{\text{mm}^3} \))

Spindle power = \( 0.7 \frac{\text{W}}{\text{mm}^3} \times 8 \times 10^{-6} \frac{\text{mm}^3}{s} = 5.6 \times 10^{-5} \text{ Watts!} \)

Compare to 65 Watts! This process seems very inefficient.

Why? First \( U_s \) may not apply to our case, they were done on larger machines.

Possible problem - small electric motors are very inefficient compared to larger ones and cutting tool may be quite flexible and inefficient.
Micro machining example

![Graph with data points and labels indicating various materials and processes, including Injection Molding, Sputtering, and Finish Machining. A legend provides details on each symbol and process.](image)

Process Rate [kg/hr]

- Injection Molding [20]
- Sputtering [29,34]
- Dril EDM [29,35]
- Cupola Meter [28]
- Dry Etching of an Oxide Film [28]
- Brazing [37,38]
- Arc SWNT [48]
- Machining [16]
- Grinding [22]
- Laser DMD [33]
- Carbon Nanofiber Production [12]
- Dry Etching of a Nitride Film [28]
- PCB Soldering [40]
- CVD/SWNT [48]
- Finish Machining [29,33]
- Abrasive Waterjet [23]
- Thermal Oxidation [6]
- PECVD of an Oxide Film [28]
- Sputtering of Al/Cu [29,34]
- Friction Stir Weld [62]
- CVD [8,29,34]
- Wire EDM [29,32]
- Meltar [26]
- PECVD of a Nitride Film [28]
- Carbon Nanotube Production [48]
- HiPo/SWNT [44,45]
5. Injection molding redesign (XX pts)

A flat rectangular part with dimensions L x W x H is successfully injection molded at
temperature T and filling velocity V through a single end gate. A modified design of this
part has decreased each dimension by 30%. It is planned to mold this part at the same
temperature and velocity. A manufacturing engineer suggests that you may run the risk of
a short-shot. Do you agree? Please justify your answer with an analysis.

Here we are concerned with the ratio of the flow rate to the heat transfer rate. The flow
time can be calculated as:
\[ L = vt_{flow} \]
where \( v \) = filling velocity, \( L \) = length of part
\[ t_{flow} = \frac{L}{v} \]

The cooling time can be estimated as:
\[ t_{cool} \approx \frac{(H/2)^2}{\alpha} = \frac{H^2}{4\alpha} \]
where \( H \) = thickness of part, \( \alpha \) = thermal diffusivity of polymers \( \approx 10^{-3} \text{ cm}^2/\text{s} \)

Then their ratio for the original part dimensions is:
\[ \frac{\text{Flow rate}}{\text{Heat transfer rate}} \approx \frac{1}{t_{flow}} = \frac{t_{cool}}{t_{cool}} = \frac{H^2v}{4\alpha L} \]

For the modified smaller part, at the same temperature and velocity, the ratio is:
\[ \frac{\text{Flow rate}}{\text{Heat transfer rate}} \approx \frac{(0.7H)^2v}{4\alpha(0.7L)} = 0.7 \frac{H^2v}{4\alpha L} \]

A lower ratio implies higher possibility of a short shot (see Injection Molding lecture
notes on Non-Isothermal Flow). We can also see that just by looking at the times: for the
modified design,
\[ t_{flow} = \frac{0.7L}{v} \rightarrow 30\% \text{ reduction from original flow time} \]
\[ t_{cool} \approx \frac{(0.7H/2)^2}{\alpha} = \frac{0.49H^2}{4\alpha} \rightarrow 51\% \text{ reduction from original cooling time} \]

The cooling time decreases more than the flow time, so there is indeed risk of a short
shot (the part might solidify before the entire mold is filled).