MIT 2.008 Design and Manufacturing II
Spring 2022
March 16, 2022

- Closed Book
- All work for CREDIT must be completed in this quiz document
- You are allowed one double-sided, hand written 8.5" x 11" notes sheet
- Calculators are allowed

Name: **SOLUTIONS**

Problem 1		Out of 16 points
Problem 2		Out of 28 points
Problem 3		Out of 10 points
Problem 4		Out of 36 points
Problem 5		Out of 10 points
Total		**100 points**

Problem 1

Circle or write in the correct answer(s). **1 pt each choice (no partial credit), 16 pts total**

a) All else being equal, using a polymer that has a higher melt temperature will lead to (**higher** / **lower**) shrinkage in injection molding.

b) Improving the surface finish on a mold can help decrease flash defects. **True** / **False**

c) Increasing the crystallinity of a polymer can cause a change from rubbery to glassy at the same temperature. **True** / **False**

d) A stretch ratio of 10:1 is generally acceptable for thermoforming. **True** / **False**

e) **(Absorptivity, reflectivity, conduction, emissivity)** does not significantly impact the heating time in a thermoformed part.

f) You mill a pocket with a given set of parameters (depth of cut, width of cut, feed rate). If you double the spindle speed, while holding all other parameters the same, the power required (**stays the same** / **doubles**).

g) You are turning a part on a lathe with a constant surface speed, feed, and depth of cut. If you step down to a new diameter that is half of the original diameter, the cutting force (**decreases** / **stays the same** / **increases**).

h) In machining, it's possible to have zero thrust force. **True** / **False**

i) Molten polymers are (**shear thickening** / **Newtonian** / **shear thinning**) fluids.

j) Molten metals have a **(higher / same / lower)** thermal diffusivity than polymers.

k) Die casting requires **(larger / smaller)** runner cross sections than sand casting.

l) Die casting can have internal cavities. **True** / **False**

m) The insertion force for press fit is linear with press depth. **True** / **False**

n) Increasing the frequency at which you take sample means would decrease the distance between your UCL and LCL. **True** / **False**

o) With regards to process control, it is possible to be in control but out of spec. **True** / **False**

p) Your tolerances always have to be +/- 3 sigma. **True** / **False**

Problem 2 - Injection Molding 28 pts

COVID-19 was just spiking in March 2020. You are working at Rhinostics, the company that supplies MIT their COVID test swabs, and need to analyze the manufacturing process in order to be able to produce defect-free parts as quickly as possible. Closer images of key features are also provided in **Appendix I**. The teaching staff also has several physical versions of the parts to inspect if needed. The middle of the swab is not hollow, the handle end is hollow, and the swab collection area teeth are 1 mm in height in either direction and spaced 1 mm apart.

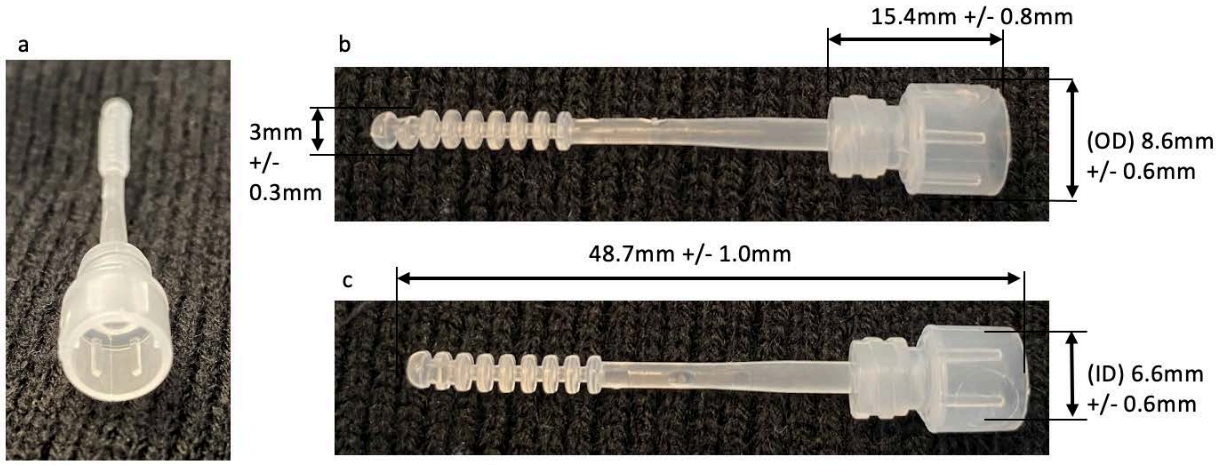


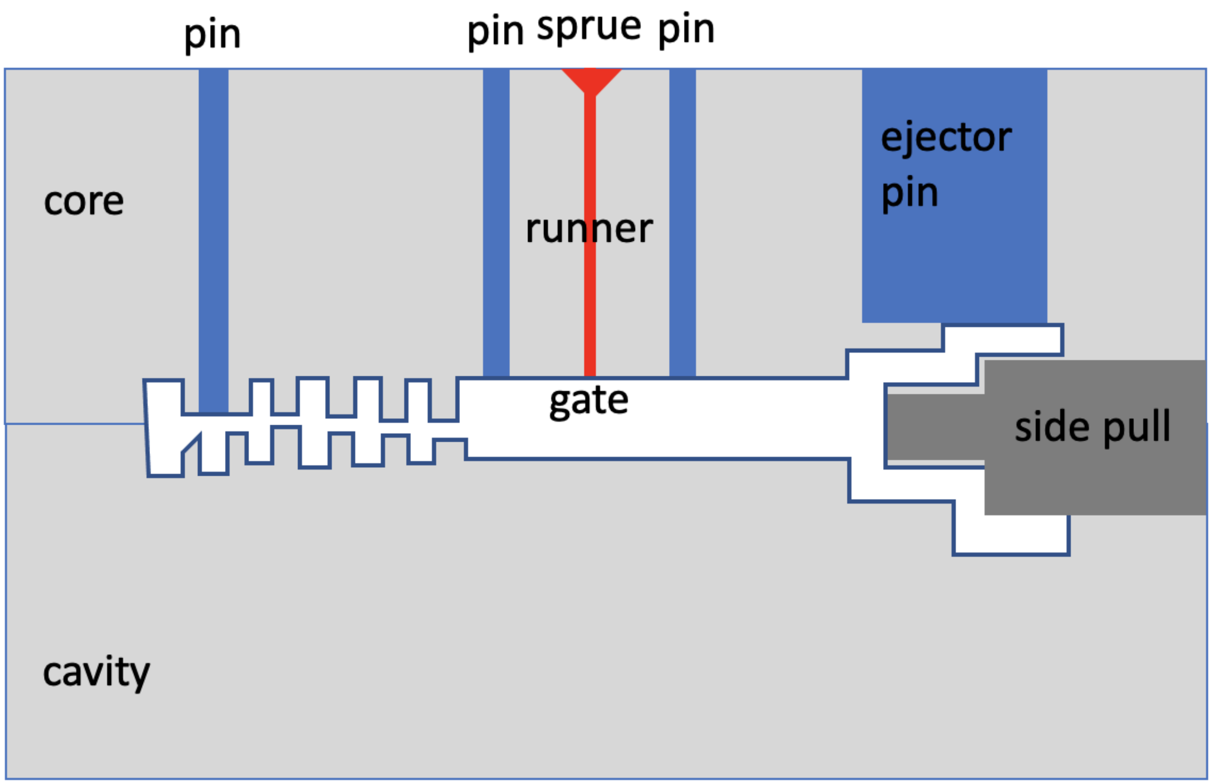
Figure 1 - Rhinostics nasal swab (a - end view, b - side-view, c - top-view)

Basic Swab Specifications:

Material:	Polypropylene
Viscosity:	1000 Pa-s
Density:	ρ = 905 kg/m^3
Specific heat:	c_p = 1920 J/kg-K
Thermal conductivity:	k = 0.16 W/m-K

a) Sketch a cross section of the mold used to make this part, **identifying and labeling** all critical features of the part and components of the mold. **11 pts**

There is a gate in the middle of the swab. This allows the plastic to flow equally to both sides of the part. A Side-pull (three-part mold) is required for the space inside the cap handle. There are 4 games, two in the middle, one at the end of the swab, and a big one at the top of the handle.



1 pt core/cavity
1 pt core is side with ejector pins
1 pt part geometry as negative space
1 pt ejector pin
1 pt showing all 3/4 ejector pins
1 pt runner
1 pt sprue
1 pt gate
1 pt parting line
2 pt side pull

b) Estimate the clamping force for a single part. Ignore the teeth and just consider the simplified geometry of the cap and the main swab as shown in Figure 2. The pressure drop in the part is 70 MPa. What is the maximum number of parts that you could produce in a single mold with the BOY XXS that has 80kN maximum clamping force? **3 pts**

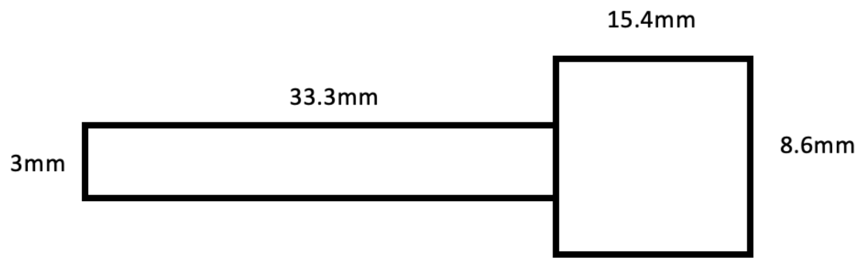


Figure 2 - Swab geometry simplification

We know that the parting line cuts the swab in half. This means that looking down at the part we see the projected area that is the length of the swab added to the cap area.

A = (0.0154m*0.0086m)+(0.0333m *0.003m) =0.00023234 m^2

$$F_{clamp} = \Delta PA = 7 * 10^7 Pa \ * \ 0.00023234\, m^2 = 16.2kN$$

We could make up to 4 parts at a time in a multi-part mold because 16.2*5 is just above our 80kN threshold where we are limited by the maximum clamp force. We didn't provide the shot size but that is another limiting factor of injection molding machines.

1 pt correct area
1 pt force formula/calculation
1 pt 4 parts (not 5)

c) Estimate the maximum number of swabs that you could produce in an hour assuming that all other cycle time contributions besides the cooling time are negligible and that $(T_{melt} - T_{mold}) \approx 10(T_{ejection} - T_{mold})$. **6 pts**

To answer this, we must calculate the cooling time (cycle time under these approximations).

$$t_{cool} \approx \frac{h^2}{4\alpha} = \frac{(905\frac{kg}{m^3})(1920\frac{J}{kg*K})(0.003\ m)^2}{4(0.16\frac{W}{m*K})} = 24.4\ seconds$$

This is the size of the middle swab which is not hollow. The only option for us to change would be the thickness of the middle swab and we would have to reduce it to 1mm to match the rest of the largest thicknesses. Now we can divide this cycle time by the hour time allotment to get the number of cycles per hour.

(60 minutes/hour) * (60 seconds/minute / 24.4 seconds/part) = 147 runs per hour.

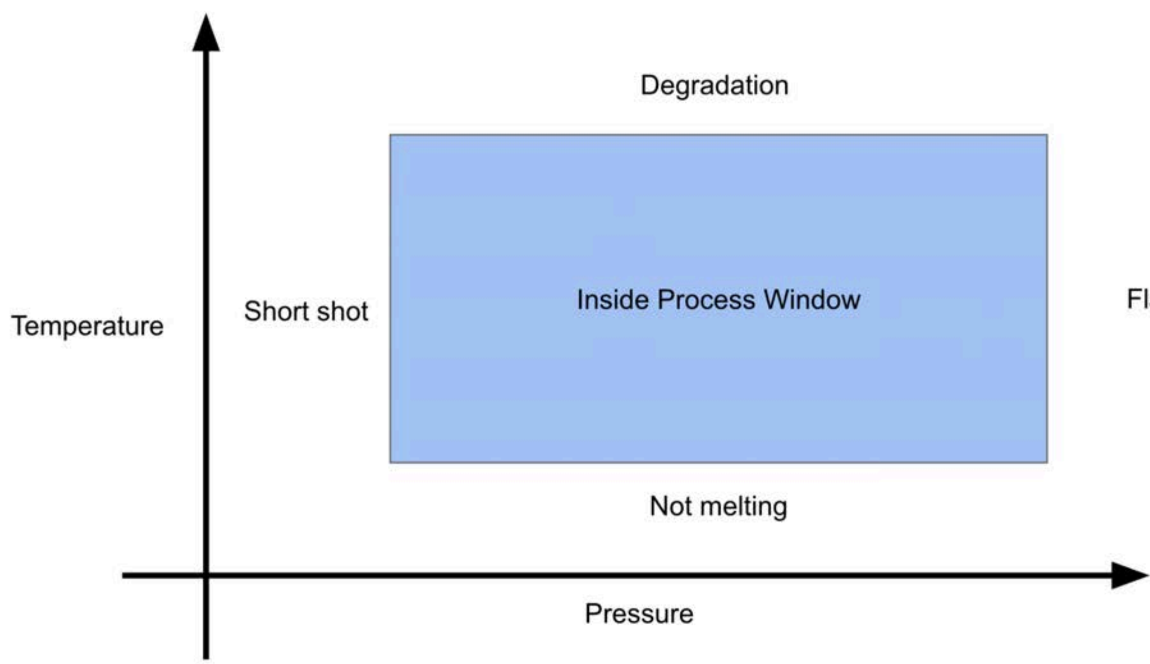
But remember that our mold can have up to 4 pieces in it so 147*4 = 588 parts per hour

2 pt using 3mm characteristic thickness
1 pt simplified formula
1 pt calculation with diffusivity
1 pt hourly rate calculation
1 pt x4 parts/mold

d) Upon first manufacturing, there was a significant flash on the end of the swab. Why is that problematic for this particular part given its use? Propose 3 ways to fix the flash using different injection molding parameters and mold/material properties. For full credit, also use a process window to defend your answer. **5 pts**

The flash on the end of the swab would cause issues with collection making it difficult to properly swab your nose and store the sample. It might also have issues connecting with the testing equipment.

There are several ways to fix the flash, primarily through the pressure drop equation seen above considering we are to the right of the process diagram for pressure. However, depending on the geometry of the window, temperature changes will likely still have an impact especially considering viscosity has a temperature component.



Pressure: The most obvious answer is to use less pressure or even move to a lower rated machine as this might no longer be effectively using the original specifications.

Temperature: You might be able to use lower temperature during injection so that the head of the flow freezes earlier in the channel.

Geometry: You could also redesign the part so that the pressure drop is higher at the end of the part (effectively making that end very thin). This could also be possible by making the swab longer since that will change the L/h ratio.

Viscosity: You could also increase the viscosity, making it more difficult to flow and increasing the pressure drop.

1 pt flash scrapes nose
1 pt process window
1 pt method 1 from any above
1 pt method 2 from any above
1 pt method 3 from any above

a) You acquire a larger machine and design an 8-part mold by creating a linear array of swabs as seen below in Figure 3. What types of differences (defects) would you expect between parts 1 and 2? Describe what would be a better layout for the multi-part mold, considering both those defects and space efficiency? **3 pts**

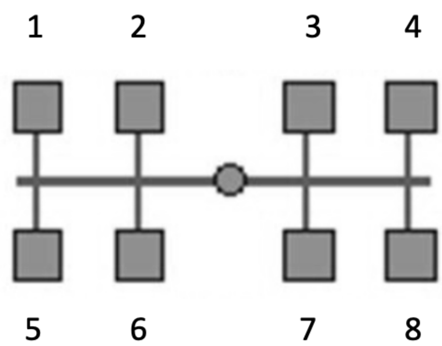
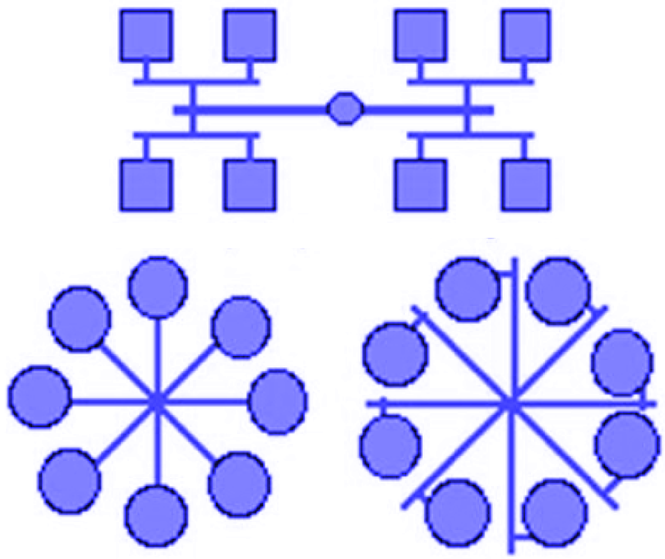


Figure 3 - Multi-part swab mold layout

We want the distance between the sprue and the part to be the same for all units. The difference between #1 and #2 would be that the molten material has cooled longer before reaching #1 and also had to travel further so required a larger injection pressure to reach. You are at risk of a short shot on the parts at the end. In terms of a redesign, while the radial one is more efficient in terms of space, any of these options are acceptable.



1 pt longer distance to 1 than 2
1 pt either short shot on 1 or flash on 2
1 pt any of the three eqiu-distant options
+1 pt (bonus) radial array might be cost prohibitive with the side pull so linear is better

Problem 3 - Casting 10 pts

While many high end bicycles use cold forged aluminum alloy or carbon composite cranks, cast aluminum alloy cranks are widely utilized in high volume, low cost applications. Figure 4a shows a rider on a bicycle and 4b shows detail of the drive side crank and chainring.

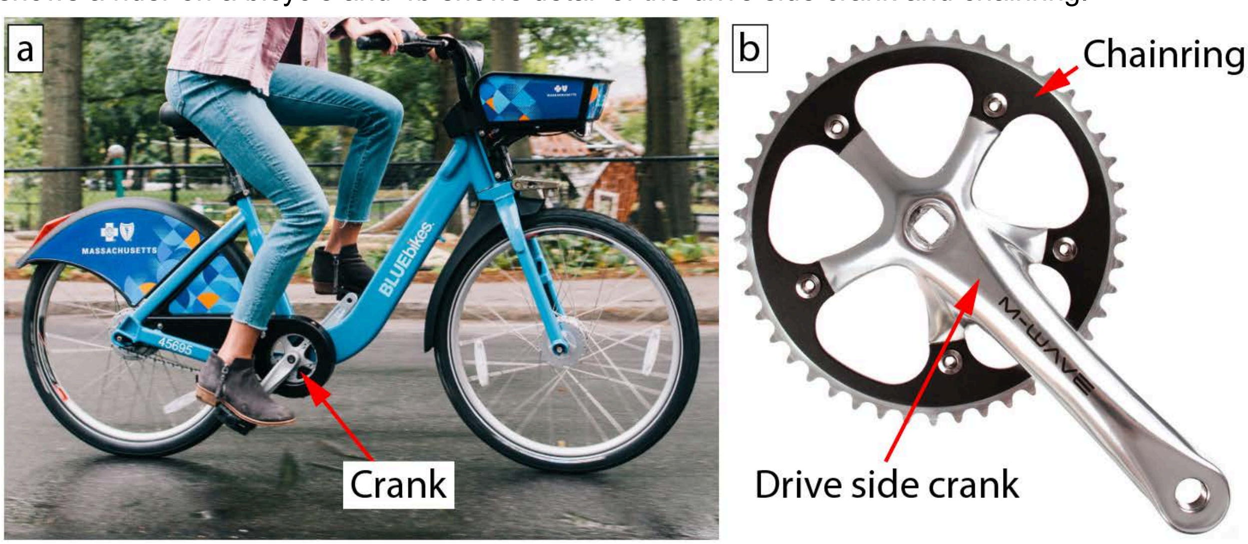


Figure 4: (a) Cyclist pedaling a crank and (b) drive side crank and joined chainring.

Shown below in Figures 5-8 is the drive side crank of a cast crankset, consisting of an arm and an integrated spider (the features that hold the chainring).

Figure 5: Drive side crank with dimensions.

Figure 6: Isometric view of drive side crank.

Figure 7: Backside of drive side crank.

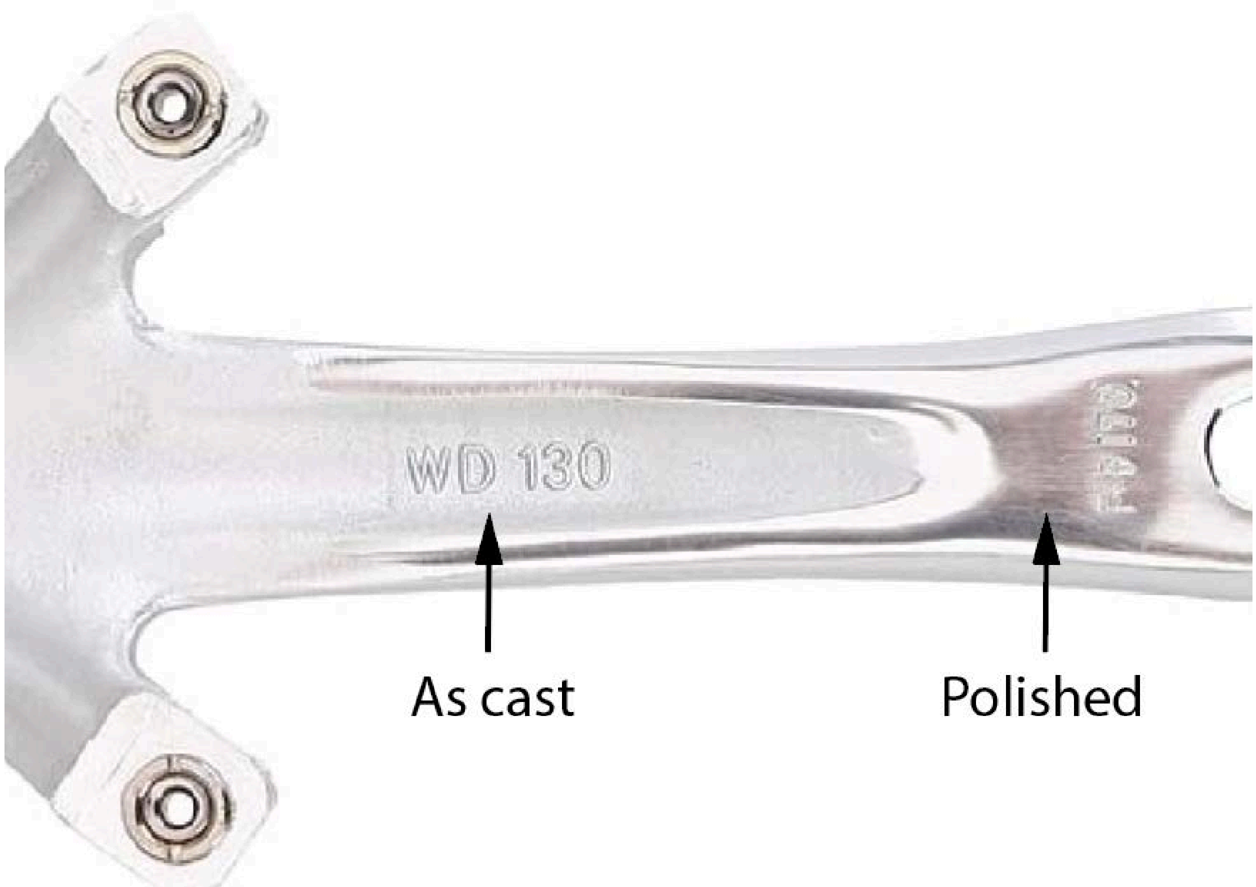


Figure 8: Backside detail of drive side crank.

a) As shown in Figures 3 and 4, the crank has a maximum length of 260 +/- 0.1 mm, a total width of 150 +/- 0.1 mm, a volume of 150 cm^3, and a surface area of 260 cm^2. Given these specified dimensions, what would you estimate to be the solidification time to be for the part?
For an aluminum alloy part and sand mold, use a constant C = 84.7 s/cm^2, or for an aluminum alloy part and steel mold, use a constant *C* = 1.4 s/cm. **6 pts**

Because of the tolerances of the part, the part must be die cast. Additionally, the complex parting line would be difficult to achieve with sand casting.

Use Chvorinov's rule for die casting: $t = C\left(\frac{V}{A}\right)^1$

$$t = 1.4\ (s/cm)\left(\frac{150\ cm^3}{260\ cm^2}\right)^1$$

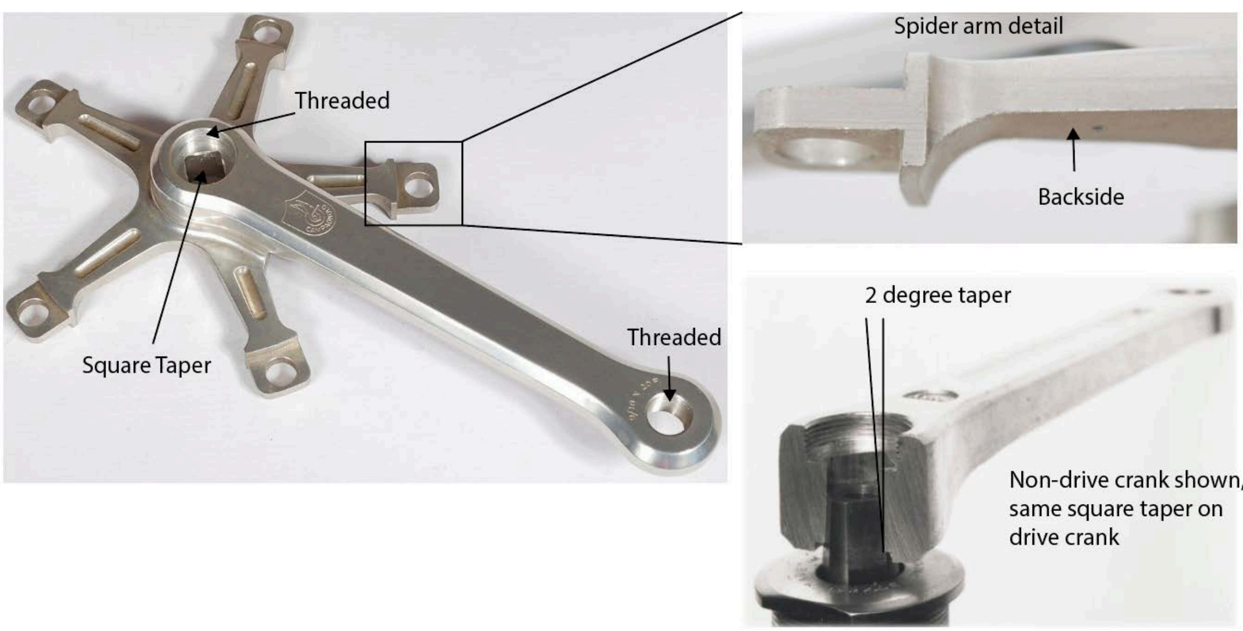
t = 0.81 s

+3 say sand cast because of the surface texture and correctly calculate the time for sand casting.

b) While cast cranks find application in lower cost bikes, they are not suitable for high performance bikes with riders capable of generating a lot of force. Provide a reason for why this is the case. **4 pts**
Cast parts can have defects such as microcracking or porosity which lead to low strength and potential for catastrophic failure of the part when under high load.
Slow cooling times generally result in larger grain structures which negatively affect the strength of the part. While die casting allows for a quicker cooling time than sand casting, and therefore a more favorable grain structure, the grain structure / part strength is still inferior to those parts forged or machined from a billet.

Problem 4 - Cutting 36 pts

You run a small bicycle manufacturer. A combination of high demand and massive supply chain and shipping delays have resulted in you being out of cranksets for your bike building operation. The vendor estimated that it will be 5 months until they can ship you more cranksets. As this is the only part that you are missing, and you have a backlog of bike orders waiting to be fulfilled, you consider quickly supplementing crank production with CNC machined parts, similar to the Campagnolo cranksets widely used in the 70's and 80's.



a) The drive side crank has a volume of approximately 150 cm^3 and your stock is 27 x 16 x 4 cm. You have a number of HAAS VF-2SS CNC machines available to use, with spindles rated at 22.4 kW and 12,000 rpm. You are using a 12 mm diameter, 3 flute end mill. The range of machining conditions for aluminum alloys are a feed of 0.08 - 0.4 mm/tooth and a cutting speed of 300-3000 m/min. For your high efficiency milling application you choose a feed of 0.2 mm/tooth, a depth of cut of 20mm, and a width of cut of 3 mm. Additionally, the specific energy of your aluminum alloy is 0.8 W*s/mm^3. How long would you estimate the rough machining operation of the drive side crank to take? **16 pts**

i) Calculate volume to remove:
Stock = 27 cm x 16 cm x 4 cm = 1728 cm^3
Volume to remove = Stock - part = 1728 cm^3- 150 cm^3 = 1578 cm^3
4pts

ii) Calculate max surface speed to make sure it is acceptable:
V = pi*D*N
V = pi* 0.012 m * 12000 rpm = 452 m/min (OK!)

iii) Calculate linear speed of workpiece (feed rate)
v = f * N * n
v = 0.2 mm/tooth * 12000 rpm * 3 flutes(tooth) = 7200 mm/min
4pts

iv) Calculate MRR
MRR = w * d * v
MRR = 3 mm * 20 mm * 7200 mm/min = 432,000 mm^3/min
4 pts

v) Time = volume to remove / MRR
Time = 1,578,000 mm^3 / 432,000 (mm^3/min) = 3.65 minutes = 219 s
4pts

Some students may perform an alternative calculation using power and specific energy, though it would not be possible to reach this MRR given the stated spindle speed, feed, and tool combination. Also note that rated power =/= machining power.

b) Given your estimate, how would you expect the actual machining time to compare? Support your answer with a brief description of a process plan for machining the part. **10 pts**
This estimate is much faster than what would likely be the actual machining time.

A possible process plan would be:
i) Set up the stock
ii) Rough mill with a flat end mill the top side of the crank
iii) Mill the two holes (pedal thread and bottom bracket cover)
iv) Change tool (chamfer cutter) to mill the chamfer
v) Change tool (small ball mill) to mill the small pocket on the spider arms
vi) Change tool (end mill or drill) to drill the 5 holes on the spider arms)
vii) Change tool (tap) cut the 2 threaded features

viii) Flip workpiece and re-fixture
ix) Change tool (end mill, probably bull nose) and mill back side of arm
x) Mill square taper hole
xi) Remove part, etch logos, and polish

c) How would you expect the rate, quality, cost, and flexibility of milling and casting processes to compare for producing a part like the crank? What process would you use if you were a small builder producing 100 bikes per year, or a large builder producing 10,000 bikes per year? **10 pts**

	Process	
Attribute	**Milling**	**Casting**
Rate	Low	High
Quality	High	Low
Cost	High	Small Quantity - High Large Quantity - Low
Flexibility	High	Low

For 100 bikes we would use machining since the setup is flexible and has low capital cost assuming that you can rent time on a mill. For 10,000 bikes, it is worth investing into a mold for die casting to improve the rate and cost of the part, assuming that the quality still meets the design requirements.

1 pt for each segment
1 pt for each process suggestion

Problem 5 - Variation / Quality Control 10 pts

Refer to the dimensioned drawing of the nasal swab above and focus on the cap diameter. Those tolerances were set so that you would only scrap 1.24% of parts out of specification. Refer to **Appendix II** for z-tables if needed.

a) Assuming a centered process, what must be your process standard deviation? **6 pts**

$$Z = \frac{x - \bar{x}}{s}$$

1.24%=0.00164/2=0.0062=Z(2.5)
s = (x-xbar)/Z = (9.2mm-8.6mm)/(2.5) = 0.24

1 pt 1.24% is the percentage
1 pt 1.24%/2 on each side
1 pt Z(2.5)
1 pt 0.6mm tolerance
1 pt formula rearrange
1 pt calculation

b) What is the Cpk? **2 pts**

Cpk = (0.6mm+0.6mm)/(6*0.24)= 0.833
or
Cpk = (2.5)/(3)= 0.833

1 pt range or Zmin (numerator)
1 pt calculation or standard deviation (denominator)

c) Just based on the 1.24% defect rate, how would you have known that the Cpk would be less than 1 without even calculating anything? **2 pts**

By definition, if the Cpk = 1 then that means we are at least 3 standard deviations from the mean which would be 99.7% and only a 0.3% defect rate.

1 pt definition of Cpk = 1
1 pt 1.24% more than 0.3%