MIT 2.008 Design and Manufacturing II

Spring 2025

Homework 1 – Injection Molding and Thermoforming

Released: February 12, 2025 2:00PM

Learning Objectives

- *Identification of key material properties for injection molded and thermoformed parts.*
- *features of injection molded (IM) parts, and how process parameters relate to common defects (the "process window").*
- *Identification of general mold design necessary to manufacture a part, based on part geometry and/or inspection.*
- *Understanding of how polymer properties (e.g. melt temperature, viscosity) relate to the selection of injection molding process parameters and part quality.*
- *Estimation of injection molding cycle time (including filling, cooling, and ejection), and understanding of how cycle time scales with part geometry and material.*
- *Estimation of injection pressure and clamping force, and use of this information to select a molding machine.*

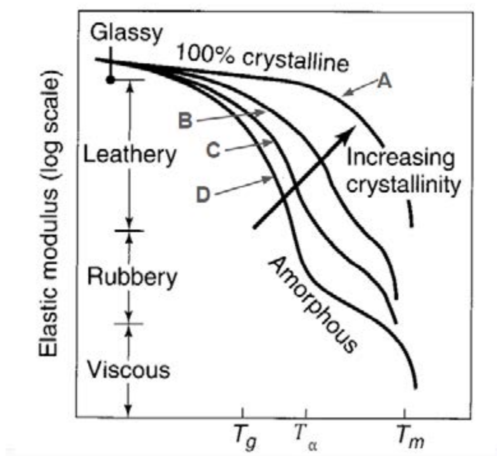
HOMEWORK TOTAL POINTS: 100 pts

Problem 1: General material properties (11 pts)

a. What is the **key difference** between a thermoplastic and a thermoset? Give one common **example of each**. Which one is more **suited for injection molding**? How about **thermoforming**? Provide brief **reasonings**.

Answer

b. You are an engineer working in the automotive industry who is trying to select a thermoplastic material to make a part that resides close to the hot engine, such that it will experience temperatures in the range $T_g < T < T_\alpha$. From the plot below, **select the material** that you will use to manufacture this part. Would you use **injection molding or thermoforming** to produce the part? Please give a brief rationale behind your choices.



Material

- ☐ A
- ☐ B
- ☐ C
- ☐ D

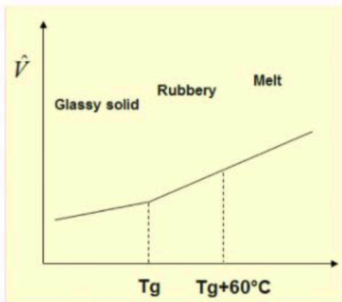
Process

- ☐ Injection Molding
- ☐ Thermoforming

Brief Rationale

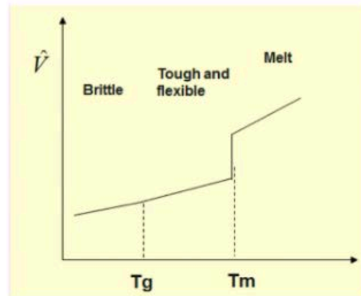
c. Shown below are two plots of Specific Volume ($\widehat{V}$) vs temperature of an amorphous and crystalline thermoplastic. Analyze the plots and answer the following questions.

Material A



Temperature

Material B



Temperature

i) Identify which material corresponds to which plot.

Material A

☐ Crystalline
☐ Amorphous

Material B

☐ Crystalline
☐ Amorphous

ii) Why is there a sharp drop in $\widehat{V}$ for Material B when cooled down from above to below T_m ?

☐ Weak bonds between the polymer chain dissolves
☐ Strong chemical bonds between the monomers within each chain dissolve
☐ The polymer chains are rearranged into structured formation/lattice structure

iii) How do you think this sharp drop in in $\widehat{V}$ as discussed in (b) may affect warpage ? Provide a brief rationale.

☐ Material B is less prone to warpage
☐ Material B is more prone to warpage

Brief Rationale

Problem 2 – Injection Molding (55 pts)

An example of an injection molded part is the arrow from the Fisher Price toy, the See 'n Say. This arrow fits onto a gear system inside the toy via a tapped hole (added after injection molding) and spins around to choose the animal noise. It is made with **HDPE (polyethylene)** that has the properties listed below in the table along with dimensions. The following questions will discuss important considerations for its design for manufacturing as well as potential defects. Key definitions are provided with important equations in **Appendix I**.

Property	**Value**
Density	$\rho = 900\ kg/m^3$
Specific heat (plastic)	$c_p = 1500$ J/kg-K
Thermal conductivity	$k_{plastic} = 0.3$ W/m-K
Glass transition temperature	$T_g = -100^oC$
Melt temperature	$T_m = 130^oC$
Height (center cylinder)	20mm
Width (maximum)	40mm
Length (end-to-end)	80mm
Thickness (solid cylinder)	3mm
Thickness (rest of part and face)	1mm
Viscosity of Molten Polyethylene (@ 130 C)	0.35 Pa•s

a) Annotate the images below to identify **3 of the following major features** (gate marks, parting lines, ejection pin, side action, support structures, etc.) that classify this as an injection molded part. Larger and additional photos are provided in **Appendix II**.

b) Design the mold that could be used to make this part. Include rough sketches of the mold and make it clear how the pieces fit together. Show the **major** features if present: gate marks, parting lines, ejection pin, side action, support structures. **(Hand drawn sketches of the assembly are sufficient. The sketches do not need to be to scale so long as major features that identify it as injection molded are identified in the sketch).**

c) Please answer the following questions that investigate the impact of the center cylinder on the injection molding process and parameters required.

i. Describe why you would expect sink marks to be present near or on the center cylinder. Where in the part will it be visible?

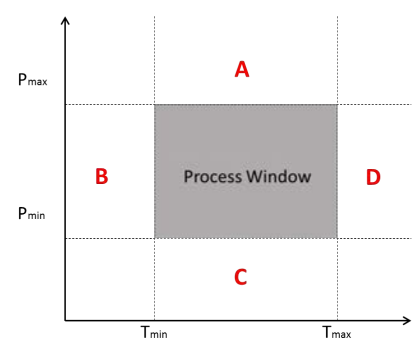
ii. How could you change the design of the center cylinder to reduce the cycle time? What effect would that change have on the mold design and will it require a side pull?

iii.What is the maximum cooling time reduction possible from that center cylinder alteration? Note: Derive an expression of the cooling time as, given the assumption ($T_{melt} - T_{mold}$) ≈ 10 ($T_{ejection} - T_{mold}$) and then use the final expression for calculation to calculate present cooling time and the new cooling time to obtain a difference. *Tip: Refer to Appendix I.*

d) Consider the design of the part/mold with regards to potential defects.

i. Would you expect weld lines to be present for this part as currently shown? If so, where would they occur?

ii. Please answer the following questions.

i) What is the flow path ratio of this part?	
ii) What does your answer in (i) suggest about the potential defect?	
iii) Without changing the design of the part or tooling, name at least two ways to eliminate this issue. Defend your answer with a process window. (has been provided for your convenience)	

Space for calculations/further description:

e) Please answer the following questions.

What is the required **clamping force**? Assume the pressure needed to injection mold this part is 50 MPa.	
How would your answer change if you made the **alteration to the center cylinder** from the earlier question?	
Considering the amount of waste plastic generated by these toys, Fisher Price is being pressured to use biodegradable polymers. One formulation has all the same properties as the HDPE listed above, but the **viscosity is double**. How would this affect the clamping force?	

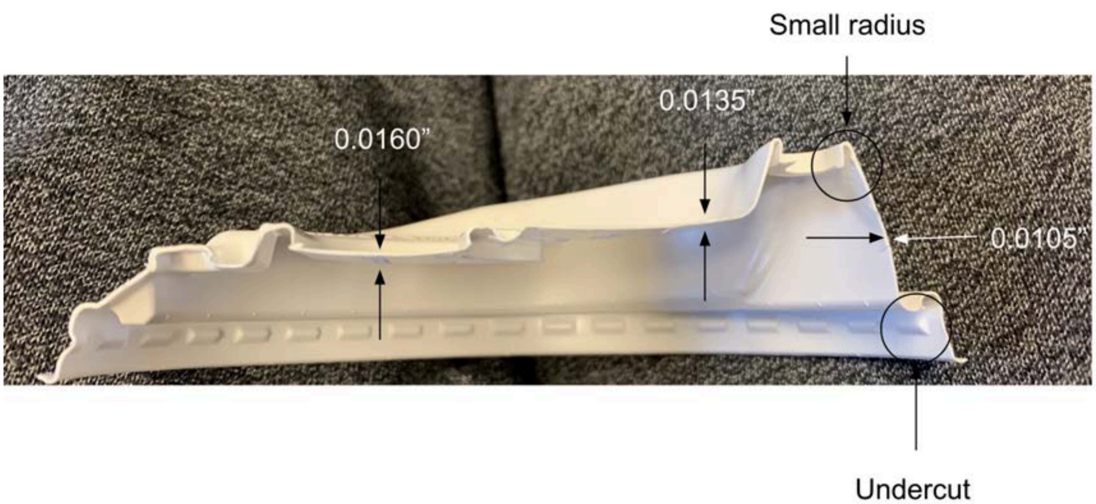
Space for calculations/further description:

f) The Quality Control department is concerned about shrinkage in the part. Choose from the following options (increase, decrease, or stay the same) for the relationship between these key parameters and shrinkage. Defend your answer with the temperature and pressure history of an injection molded part.

Manufacturing Action	Will shrinkage…. increase, decrease, or stay the same	Rationale
Increase Melt Temperature		
Increase Mold Temperature		
Increase Injection Rate		
Increase Packing Pressure		
Increase Packing TIme		

<u>Problem 3 – Thermoforming</u> (34 pts)

Consider the manufacturing process of a coffee lid, as shown below. Part has a diameter of ~ 3.5 inches and is made from Polypropylene (PP).



a) What features suggest that this part is thermoformed? Provide 3 or more reasons why this part is not injection molded. Tip: Use dimensionless number, where applicable for explanation.

Reason 1	
Reason 2	
Reason 3	

b) What region of the coffee lid had the **most amount of strain**? What region had the **least strain**? Explain below.

c) The lid is made of polystyrene. It has a glass transition temperature of 95°C and a melt temperature of 200°C. For each of the following forming temperatures, decide if the thermoforming would be successful or what would happen to the part. If multiple temperatures are feasible, determine which would be the fastest process.

Temperature	**Will it be successful ?**	**Justification of why it will/will not be successful. What will happen to the part ?**
70°C		
120°C		
170°C		
220°C		

d) Consider how the part was thermoformed and draw the thermoform tooling. Indicate the key features in the tooling necessary for thermoforming of the part, based on what you observe about its geometry. For this question, do not consider any post-processing of the lid, just the main forming step.

e) Consider Quality/Cost/Rate/Flexibility of Thermoforming vs Injection Molding. Circle which one is higher for each factor and provide a brief rationale.

Factor	Which one is higher?		Rationale
Quality	Injection Molding	Thermoformin g	
Cost	Injection Molding	Thermoformin g	
Rate	Injection Molding	Thermoformin g	
Flexibility	Injection Molding	Thermoformin g	

Appendix I: Key Formulas and Definitions

Injection Pressure

Expression for pressure drop ΔP in a flow between two parallel plates:

$$\Delta P = \frac{12\mu Q L}{w h^3} = \frac{12\mu}{t_{fill}}\left(\frac{L}{h}\right)^2$$

μ = viscosity of plastic

Q = flow rate

h = thickness of channel or mold cavity

w = width of channel (much larger than thickness h)

L = length of mold channel or cavity

t_{fill} = time needed to fill mold

Clamping Force

For a certain pressure drop across the mold of ΔP, the average clamping force for a mold is given by:

$$F_{clamp} = \Delta P\, A_{mold}$$

F_{clamp} = clamping force

A_{mold} = projected area of part = wL

Cooling Time

Exact analytical solution of cooling via conduction:

$$t_{cool} = \frac{h^2}{\pi^2 \alpha} ln\left(\frac{4}{\pi}\,\frac{T_{melt} - T_{mold}}{T_{ejection} - T_{mold}}\right)$$

With $\alpha = \frac{k}{\rho\, c_p}$

α = thermal diffusivity

k = thermal conductivity

c_p = specific heat capacity

ρ = density

h = characteristic part thickness

Approximation:

$$t_{cool} \approx \frac{h^2}{4\alpha}$$

If the following is satisfied: $(T_{melt} - T_{mold}) \approx 10\,(T_{ejection} - T_{mold})$

T_{melt} = melt temperature (temperature of polymer at the start of injection)

T_{mold} = mold or wall temperature

$T_{ejection}$ = ejection temperature

Radiative Heating

By conservation of energy, $t_{heating}$ is the time required to heat up a uniform substrate to a forming temperature:

$$t_{heating} = \frac{\rho h c_p}{aP}\left(T_{forming} - T_{initial}\right)$$

a = absorptivity coefficient of the substrate

P = lamp power per unit area

Appendix II: Additional Part Pictures