MIT 2.008 Design and Manufacturing II

Spring 2025

Homework 7 – Forming, Casting & Layered Manufacturing

Released: April 23rd, 2025 2:00 PM

Learning Objectives

- *Understanding principles of various casting methods and being able to apply heat transfer and fluid mechanics to perform basic sizing calculations related to casting.*
- *Understanding material structure, and parameters that dominate metal forming.*
- *Understand, at a high level, various layered manufacturing processes ranging from common 3D printing processes to various processes in electronics manufacturing.*
- *Gain some experience with applying first principles to do back-of-envelope calculations related to sand casting and die casting.*
- *Gain some experience with identifying/characterizing products made from various layered manufacturing processes (3D printing, etching, PVD, CVD, etc.)*

General Notes

- *For qualitative answers, we're not looking for long essays. Please answer using short (1-2 sentences per answer) bullet points.*
- *For quantitative answers, show your work as clearly as possible. When possible, keep answers in algebraic form until plugging in numbers at the very end; this way, it is much easier for graders to understand where you make mistakes and provide meaningful feedback.*

HOMEWORK TOTAL POINTS: 100 pts

Problem 1 – Short Questions

Please choose the correct option(s) below. Please give a brief rationale behind your choice(s). *Note: There* ***can be more than one correct answer*** *for each question. Provide a brief rationale where required (boxes provided).*

a. What are the reason(s) of the limited accuracy and repeatability of the sheet metal bending process?

- ☐ The cost and equipment of highly precise and accurate dies are too expensive
- ☐ Elastic recovery of metal usually leads to springback effect which leads to loss in accuracy/precision.
- ☐ Bending is usually done by technicians who manually operate dies, which leads to loss in accuracy/precision.
- ☐ The bending process is sensitive to many variabilities ranging from setup/fixturing of work material, material properties, fine turning/calibrating the process .

b. For forming operations, material strength and ductility are two important parameters and are dependent on metal grain sizes. Choose the best answer(s):

- ☐ Increasing metal grain size increases strength and decreases ductility.
- ☐ Increasing metal grain size decreases strength and increases ductility.
- ☐ Increasing metal grain size increases strength and increases ductility.
- ☐ Increasing metal grain size decreases strength and decreases ductility.

Rationale

c. You are designing a jet engine turbine blade. Which process would you use for the manufacturing of this part and why?

- ☐ Sand Casting
- ☐ 3D Printing (Powder Bed Fusion)
- ☐ Investment Casting
- ☐ Die Casting

Rationale

d. After you have designed a mold for die casting for a ~1 inch diameter pipe, your manager asks you why you have made the runners/sprues almost as big as the pipe itself? He says “Go make the runner/sprues smaller, maybe 1% of the diameter of the pipe. The price of metals has sky-rocketed recently”. Which of the following response(s) would you give as a good engineer?

- ☐ You’re right, it doesn't need to be that big. I can make it smaller!
- ☐ Well acktually, we can remelt and reuse the metal in the runner/sprues to save money!
- ☐ It needs to be very big so that turbulent flow can be avoided, since turbulent flow introduces defects in the part while solidification occurs.
- ☐ There may be a chance of a short shot due to shrinkage and premature solidification. I need to do further analysis to see how much smaller I can make the runner/sprue diameter.

Rationale

e. Which of the following semiconductor fabrication operation(s) are **additive**:

- ☐ Physical vapor deposition (PVD)
- ☐ Chemical vapor deposition (CVD)
- ☐ Wet etching
- ☐ Electroplating

f. Which of the following semiconductor fabrication operation(s) are **subtractive**:

- ☐ Doping
- ☐ Oxidation
- ☐ Polishing
- ☐ Dry etching

g. Physical vapor deposition (PVD) is **best** described as:

- ☐ A film is created by a chemical reaction of gaseous precursors at the substrate surface (but not consuming the substrate).
- ☐ The surface of the wafer reacts to form a thin film; for example, oxidation. The substrate surface is consumed.
- ☐ The wafer is etched by a corrosive agent and the residual elements from the bubbles of the reaction are deposited onto the surface.
- ☐ A film is created by exposing the substrate (maintained at a lower temperature) to a vapor of the desired material (maintained at a higher temperature).

h. In electronics manufacturing, photolithography is **best** described as a process by which:

☐ A laser engraves patterns into surfaces of interest.

☐ Light of a specific wavelength (typically UV) is projected through a mask to modify the crosslinking of a photosensitive polymer in the desired regions.

☐ Patterns in a liquid film are created by radio waves, always in a periodic pattern.

☐ Text on PCB boards is printed.

i. In electronics manufacturing, etching is **best** described as a process by which

☐ Plasma is deposited onto a surface of metal.

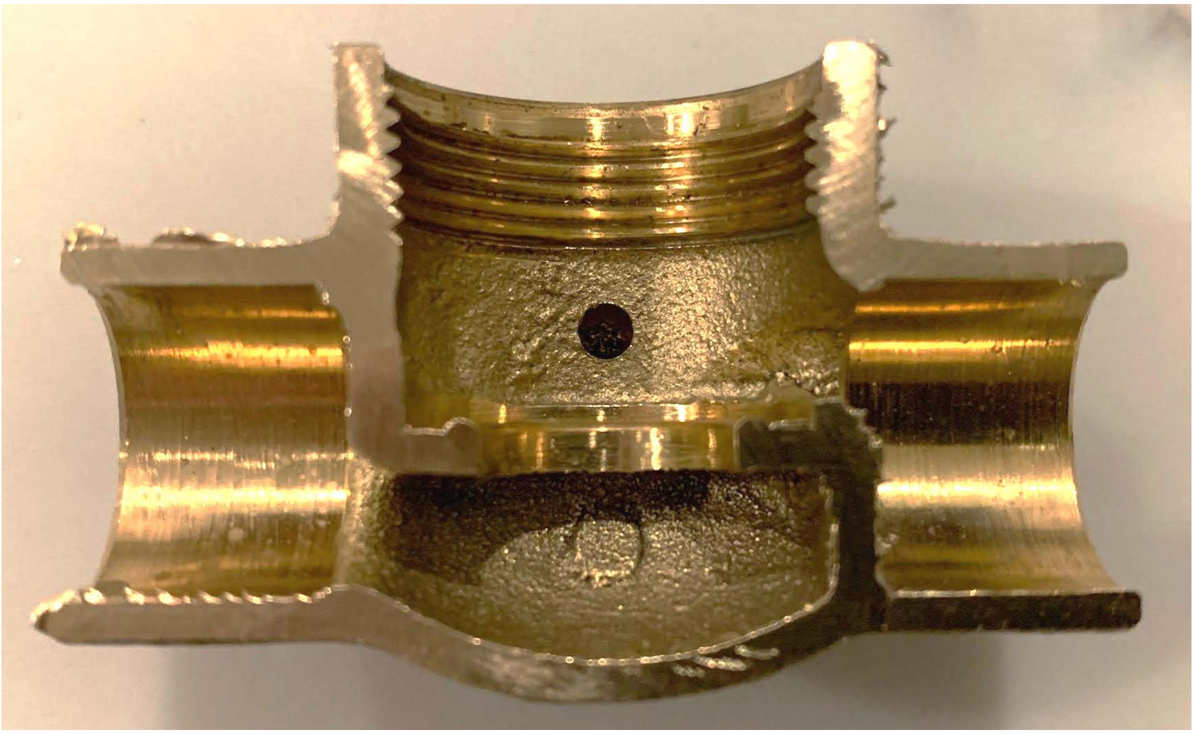
☐ (Selective) Removal of material by liquid, gas, ions, or plasma.

☐ Removal of photoresist after a patterning process.

☐ The vertical holes between different layers of copper are filled.

Problem 2 – Casting I

Consider the main body of a brass valve, shown in the photo below. For your reference, it has been cross-sectioned at its parting line to show the internal features.



a. Answer the following questions:

i) Which casting process was used for this part?	
ii) How can you tell it was made from the casting process you stated in (i)?	

iii) Why did the manufacturer choose it over the other types of casting?	

b. For the body of the valve in part (a), we will use Chvorinov's rule to estimate the solidification and cooling time for the valve body. The valve body can be roughly approximated as a hollow cylinder, OD 34 mm, ID 24 mm, and length 55 mm. The area of the ends of the cylinder are small and can be neglected. Chvorinov's rule, for die casting: $t = C\left(\frac{V}{A}\right)^1$ and for sand casting: $t = C\left(\frac{V}{A}\right)^2$. Assume $C_{sand} = 1,200,000\ s/m^2$ or $C_{die} = 80\ s/m$.

i) Calculate the cooling times if the part was **sand-casted** (*Note your assumptions*)

ii) Calculate the cooling times if the part was **die-casted** (*Note your assumptions*)

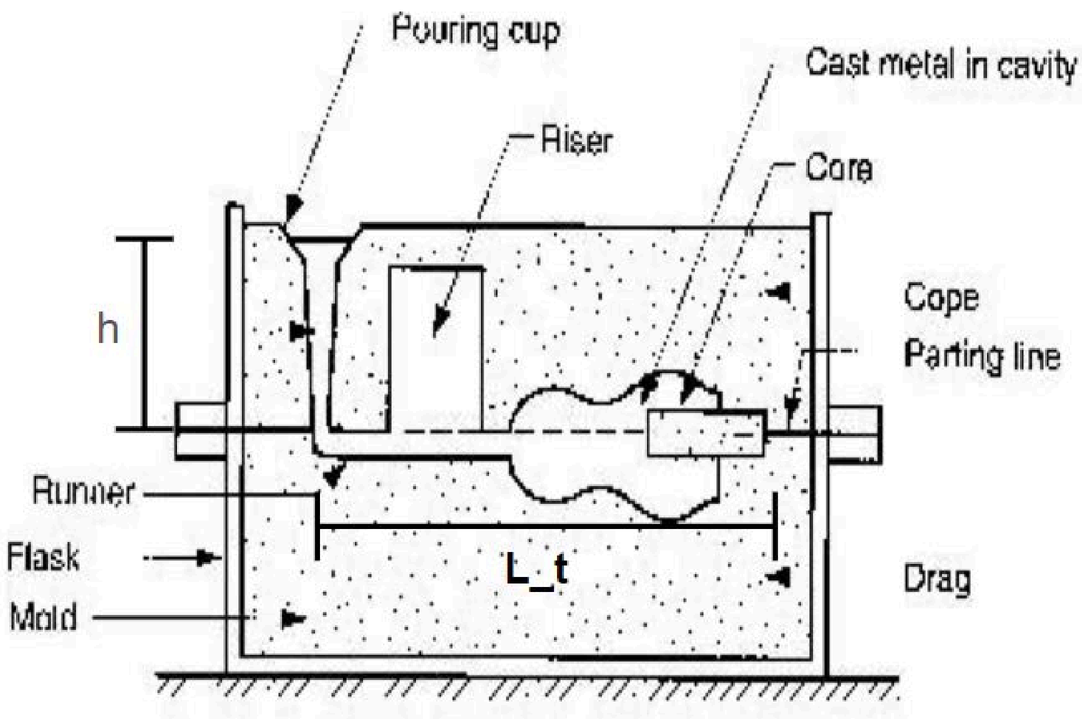
iii) Why do you think the molten metal in die casting cannot be poured in like sand-casting ?

c. There is a significant defect on some of the valves, shown in the pictures below.


i) What are some of the causes of this defect?	
ii) The valve manufacturer argues that making the riser larger will solve this shrinkage problem. Why might that be true?	
iii) Describe 2 **other** defects that might occur in a casted part like this valve.	

Problem 3 – Casting II

a) Pure aluminum is poured into a sand mold. The metal level in the pouring basin is 10in (h) above the metal level in the mold and the runner is circular with a 0.4 inch diameter. Assume total length (L_t) ~ 25 in.



Assume the system is frictionless and use the following properties for Aluminum:
Melting point: 660 C
Viscosity 1.38 mPa-s
Density 2380 kg-m^{-3}

i) What is the velocity of the flow of the metal into the mold?	

ii) What is the flow rate of the flow of the metal into the mold?	
iii) Is the flow turbulent or laminar? Will this be an issue? If so, explain why.	

b) For the sprue described in part (a), answer the following questions.

i) What runner diameter is needed to ensure a Reynolds number of 2000?	
ii) How long will a 20 in^3 casting take to fill with such a runner?	
iii) Is the time you calculated in part (ii) reasonable?	

c) Using the runner diameter calculated in part (b) to answer the following questions.

i) What is the likelihood of a short shot if die casting was utilized to manufacture this valve? Assume thermal diffusivity of steel utilized in the die-casting molding $\alpha \sim 2 \times 10^{-5}\ m^2/s$.

ii) Using the results obtained in part (i), is it a good idea to die-cast a part with this runner diameter? Why/Why not?

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Problem 4 – Forming and Additive Manufacturing Comparison

The outer body panel of an automobile is most typically made by stamping sheet steel in a series of matched-tool forming operations. However, driven primarily by the need to reduce weight, alternative materials and processes have come into use. Most common among these is the substitution of high strength, high ductility aluminum to polymeric composites such as short fiber thermoplastics and long fiber thermosets. In select cases, panels have also been made with extrusion additive manufacturing (see here for an example: the Shelby Cobra made at Oak Ridge National Labs).

In this problem, we will address some of these materials and discuss the details of the specific processes, how each material reacts to the process, and what the in-service performance of panels from these materials will be. In particular, we will consider

1. Conventional Sheet Steel Stamping
2. Aluminum Sheet Stamping
3. Large-format additive manufacturing (extrusion)

For each process, please list at least 2 bullet points which answer the following:

- The factors that influence part quality (i.e. shape fidelity, freedom from defects, material performance).
- The factors that determine or limit the production rate
- The factors that influence the cost of panels (tooling, material, secondary ops, etc.)

Assume the following:

- Steel: yield strength 250 MPa, Young's Modulus 190 GPa
- Al: yield strength 40 MPa, Young's Modulus 70 GPa
- Additive manufacturing polymers: yield strength 40-150 MPa, Young's Modulus 2-4 GPa

Note: your factors for steel and aluminum stamping will be similar because they use the same manufacturing processes; for **aluminum stamping, provide at least one comparison to steel**, based on the material properties given above.

Process	**Factors which influence quality**
Steel sheet stamping	

Aluminum sheet stamping (one comparison to steel stamping)	
Polymer Large-format additive manufacturing	

Process	**Rate limiting factors**
Steel sheet stamping	
Aluminum sheet stamping (one comparison to steel stamping)	

Polymer Large-format additive manufacturing	

Process	**Factors which influence cost**
Steel sheet stamping	
Aluminum sheet stamping (one comparison to steel stamping)	
Polymer Large-format additive manufacturing	