MIT 2.008 Design and Manufacturing II

Quiz 2 - Part A, In-Class Component

Spring 2025
May 7th, 2025

- You will have 80 minutes to complete this portion of the exam
- Closed Book, except that you are allowed one double-sided, hand-written 8.5” x 11” notes sheet
- All work for CREDIT must be completed in this quiz document
- Calculators are allowed, and we have provided them in the room. Please return them at the end of the exam.

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 **(and partial credit)**.*
- *Each subquestion (e.g. a, b, c) may have a few parts to it (**i, ii, iii**). Make sure you r**ead and answer all parts of the question.***

Name: ____________________________

Part A, In-Class Component		
Problem 1		Out of 14 points
Problem 2		Out of 50 points
Problem 3		Out of 16 points
Part B, Take-Home Component		
Problem 4		Out of 20 points
Total		**100 points**

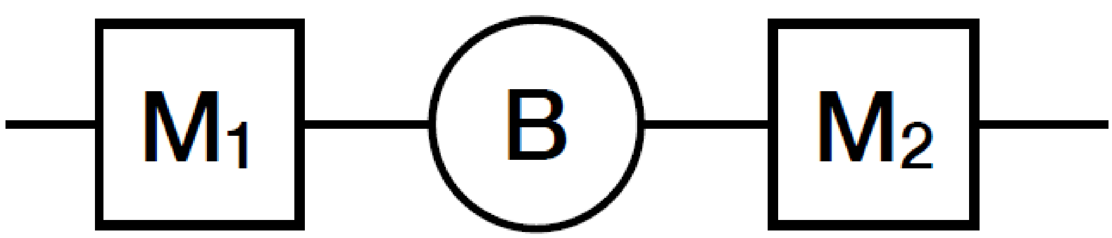
Problem 1 - Short Answers (14 points)

a) In general, to the first order, the amount of springback in a sheet-metal bending process **increases** with **(low/high)** thickness, **(low/high)** yield strength, and **(low/high)** Young's modulus.

b) For the following semiconductor processes, determine (mark with a check ✔) whether the process is considered subtractive, additive, or neither:

Process	Subtractive	Additive	Neither
Wet Etching			
Physical Vapor Deposition			
Oxidation			
Ion Implantation			
Lithography			
Metallization			
Planarization (CMP)			
Dry Etching			
Doping and Diffusion			
Characterization (e.g. surface profiling)			

c) Consider the deterministic two-machine line with an **infinite buffer** in between.



	M1	M2
Operation time (hours)	1	0.1
MTTR (hours)	100	100
MTTF (hours)	100	100

Consider the following changes **one at a time**, how would doubling each parameter affect the **overall production rate** of the line?
Provide **quantitative answers**, e.g. 0.5x, 0.67x, 1x, 1.33x, 2x, etc. of the original production rate.

Machine 1 Cycle time DOUBLES	**Production rate:_____X**
Brief rationale	

Machine 1 MTTR DOUBLES	**Production rate:_____X**
Brief rationale	

Machine 1 MTTF DOUBLES	**Production rate:_____X**
Brief rationale	

Machine 2 Cycle time DOUBLES	**Production rate:_____X**
Brief rationale	

Machine 2 MTTR DOUBLES	**Production rate:_____X**
Brief rationale	

Machine 2 MTTF DOUBLES	**Production rate:_____X**
Brief rationale	

Problem 2 - Forming (50 points)

Display technologies have progressed from CRT and LCD to OLED and now to MicroLED. While OLED displays use organic molecules deposited through solution-based processes to create light-emitting pixels, MicroLED displays utilize inorganic III-V semiconductor materials. These are typically grown on separate wafers for red, green, and blue emission, as each material system is optimized for a different wavelength.

In the MicroLED process, these emitter chips are **singulated** (cut into individual dies) and then **transferred onto a transistor matrix** that acts as the active backplane, controlling pixel operation—illustrated schematically in **Figure 1**.

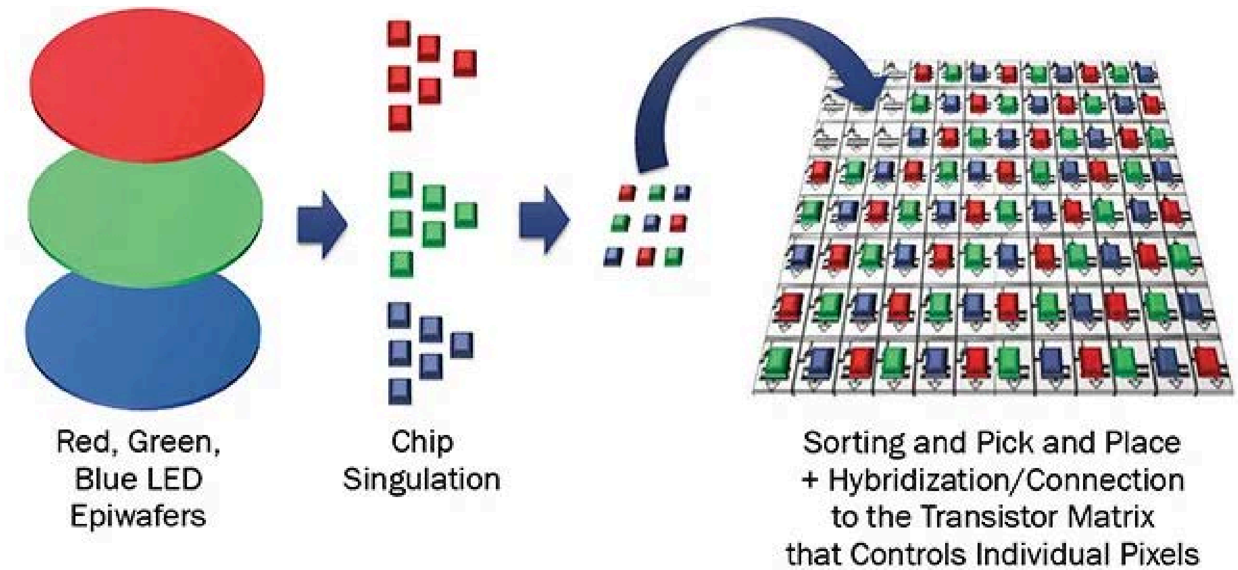


Figure 1. MicroLED pixel integration process. Singulated red, green, and blue MicroLED dies, each fabricated on separate III-V wafers, are picked and transferred onto a transistor matrix to form a full-color display.

Unlike conventional Front-End-Of-Line (FEOL) processes discussed in class, this step belongs to the **Back-End-Of-Line (BEOL) packaging**. This is an area where we **mechanical engineers can contribute**, especially in the precision mechanisms involved in chip transfer.

The **flip chip transfer process**, shown in **Figure 2**, includes a **vacuum head** that picks up singulated MicroLEDs, a **bond arm** that moves and positions the dies, and **rotating motors** that provide the necessary degrees of freedom for alignment. The MicroLED die is then flipped and bonded such that its top-side contacts align with the interconnects on the top of the transistor matrix.

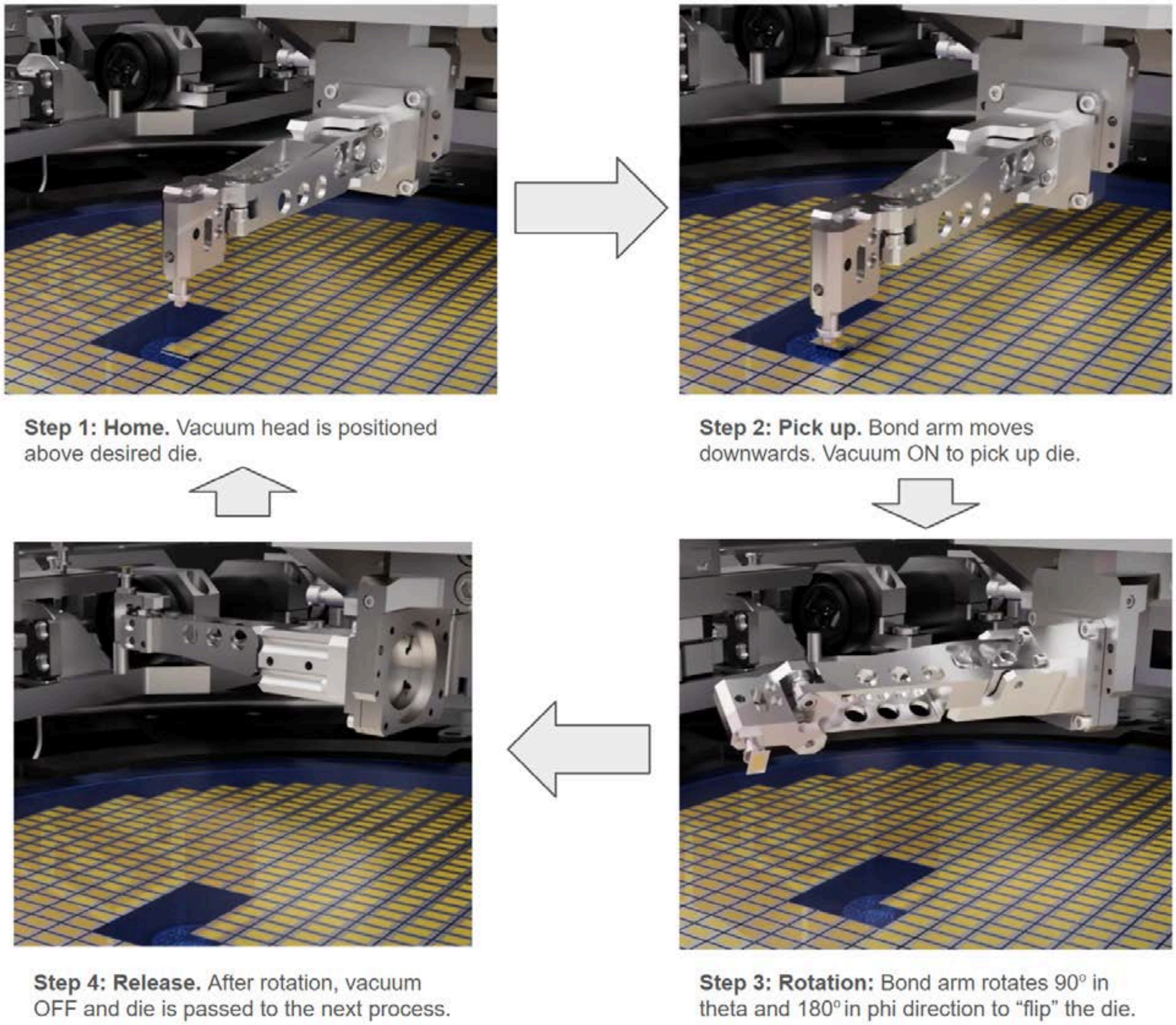


Figure 2. Schematic of the flip chip transfer process.

For this question, we focus on the **bond arm**, modeled as a beam with a constant **H-shaped cross-section**, shown in **Figure 3**. Assume the beam is currently manufactured using **machining**. Disregard mounting and joint details for now.

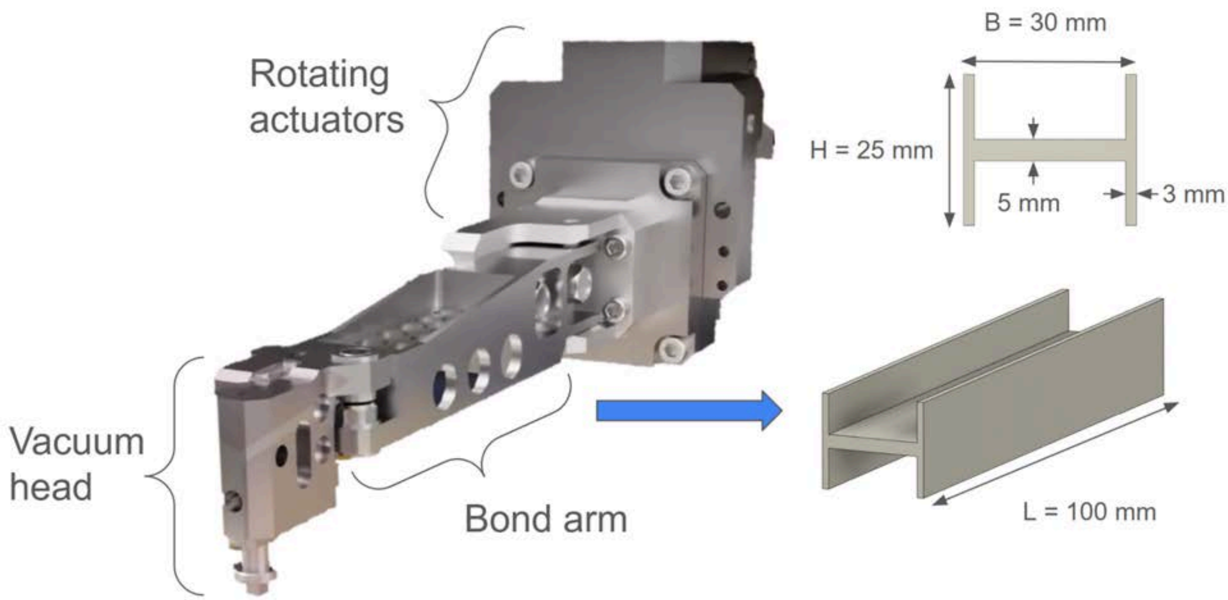


Figure 3. Flip chip assembly (left) showing a vacuum head to pick up the MicroLED die, a bond arm to position the die, and rotating motors to assist with alignment. **The simplified bond arm (right)** modeled as a beam with an H-shaped cross-section, assumed to be fabricated by machining.

a) Process Comparison: Bond Arm Manufacturing

Your task is to propose and evaluate alternative manufacturing methods for producing the bond arm beam used in flip-chip transfer tools. Focus on four manufacturing processes:

- Metal extrusion
- Sheet metal bending
- Forging
- Die-casting

Design Objective. Design a cross-section for each process that is:

- Relatively lightweight
- Structurally rigid in bending

While an H-shaped cross-section (as shown in Figure 3) is a natural choice, other viable options include U-shaped, T-shaped, or hollow rectangular sections. Solid bars are not desirable due to weight constraints in high-speed precision assembly.

Instructions. For each process, do the following:

1. **Sketch** the cross-section suitable for that manufacturing method.
2. Describe **key geometric features** that make the design manufacturable, such as:
    a. Wall thickness and thickness ratios
    b. Corner treatments (rounds, fillets, chamfers)
    c. Tapering or draft angles, if applicable
3. Explain your **rationale:** Why are these features necessary or optimal for the process?
4. Evaluate process **suitability for producing beams of approximate dimensions L=100 mm, B=30mm, and H=25mm**, as shown in Figure 3, from an **aluminum alloy.**
5. Comment on:
    a. Expected **part quality** (e.g., surface finish, mechanical properties, defect risk)
    b. Major **cost contributors** (tooling, material waste, cycle time, etc.)
    c. **Cost effectiveness at different production volumes** (low vs. high quantity)

Reference Example. A complete example is provided for the case of machining. You may frame your other answers relative to the machining example if helpful.

Machining (Reference Example Analysis)

<table>
<tr>
<td>Sketch Cross section

Describe key geometric features (wall thickness, corners, angles)

Explain how the above features contribute to manufacturability</td>
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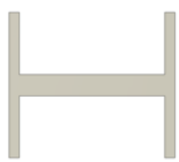

● A beam with H-shaped cross-section can be machined with an end mill in two fixturing positions (top and bottom)
● The wall thicknesses tend to be uniform for each wall but do not necessarily need to be the same between walls, as long as they are rigid enough to withstand the machining process without warping.
● Rounds and fillets are not necessary in between the middle and edge walls, but can be added using a ball or bull end mill. Chamfers on the outside edges are also optional
● Tapering and draft angles are not needed and complicates the machining process.


● A U-shaped cross-section is an alternative choice that can be easily machined on a single fixture.
● In contrast, a hollow (fully-enclosed) rectangle is not a viable option since it will be difficult to machine with an end mill.
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Suitability to produce Aluminum beam of external dimensions 100x30x25 mm (as shown in Fig. 3)	• Aluminum is readily machinable • 100x30x25 mm is a good size for machining without extremely long processing time. • The target web and flange thicknesses of 5 mm and 3 mm, respectively, provide sufficient structural rigidity from deflecting machining process.
Quality (and performance)	• **Surface finish** can be made very fine, depending on the machining parameters used. • **Mechanical performance** should be decent as the stock material is expected to be free from defects. However, the grain alignment may not favor the specific loading case.
Major **cost** contributor(s)	• **Material cost:** a **large contributor** since we are starting with a stock material with significantly more volume than the part. It is not economical or desirable to recycle the removed chips. • **Overhead:** another **large contributor** due to the long processing time. Even for the simple structures shown above, we need to machine away a large volume of material, that has an associated cutting energy that needs time for a given cutting power. • **Equipment:** potentially significant contribution to cost per part for low-volume production. **Less significant at high part quantity.** • **Tooling:** the cost of the end mills are **not significant** assuming a lightweight, easily machinable aluminum material is used for part.
Cost effectiveness vs production volume	• **Machining** is cost-effective at **low production volumes** due to the high variable costs (material and overhead).

i) Metal extrusion

Sketch **Cross section** Describe key geometric features (wall thickness, corners, angles) Explain how the above features contribute to **manufacturability**	
Suitability to produce **Aluminum** beams of external dimensions **100x30x25 mm** (as shown in Fig. 3)	
Quality (and performance)	
Major **cost** contributor(s)	
Cost effectiveness vs production volume	

ii) Sheet metal bending

Sketch **Cross section** Describe key geometric features (wall thickness, corners, angles) Explain how the above features contribute to **manufacturability**	
Suitability to produce **Aluminum** beams of external dimensions **100x30x25 mm** (as shown in Fig. 3)	
Quality (and performance)	
Major **cost** contributor(s)	
Cost effectiveness vs production volume	

iii) Forging

Sketch **Cross section** Describe key geometric features (wall thickness, corners, angles) Explain how the above features contribute to **manufacturability**	
Suitability to produce **Aluminum** beams of external dimensions **100x30x25 mm** (as shown in Fig. 3)	
Quality (and performance)	
Major **cost** contributor(s)	
Cost effectiveness vs production volume	

iv) Die-casting

Sketch **Cross section** Describe key geometric features (wall thickness, corners, angles) Explain how the above features contribute to **manufacturability**	
Suitability to produce **Aluminum** beams of external dimensions **100x30x25 mm** (as shown in Fig. 3)	
Quality (and performance)	
Major **cost** contributor(s)	
Cost effectiveness vs production volume	

b) **Sheet metal stamping and bending.** You would like to create a bond arm with a U-shaped profile with dimensions shown in Fig. 4 using sheet metal stamping and bending.

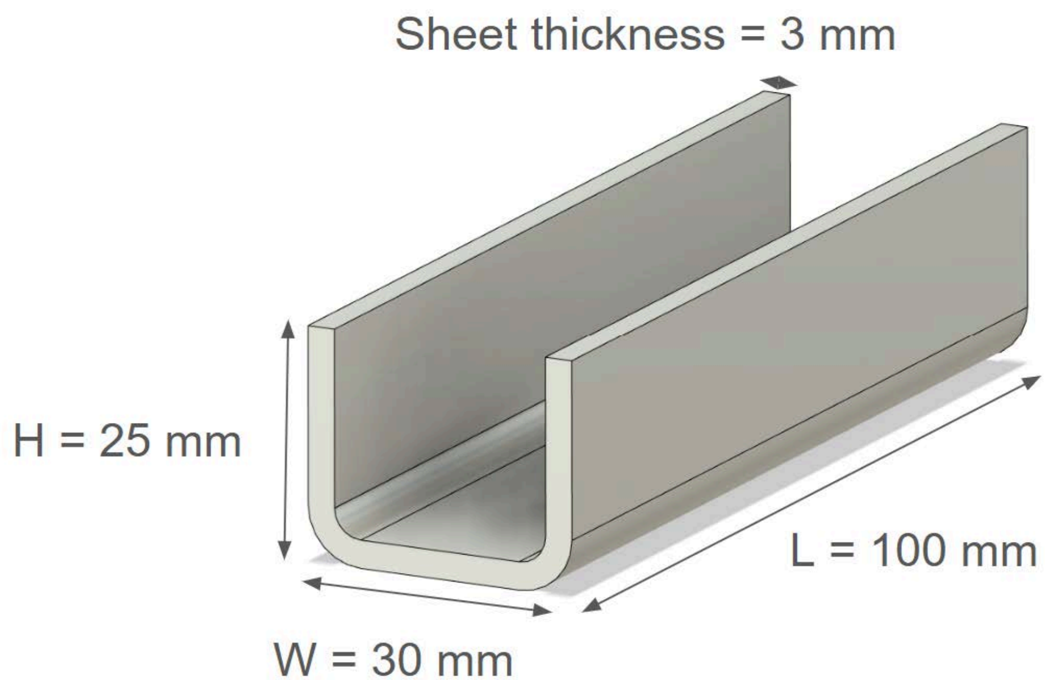

Figure 4. Bond arm made with sheet metal stamping and bending showing the desired part dimensions.

i) Using AL-5052 (properties in **Appendix 1**), what is the **shearing force** required for the stamping machine to create **one sheet** that is to be bent to the beam shown in Fig. 4?

i) You successfully stamped and bent the aluminum 5052 sheet metal to the desired shape with barely acceptable springback. Your colleague then told you that we need to reduce the wall thickness to fit a larger module inside the cavity. To reduce the thickness without sacrificing bending stiffness, you thought of replacing AL-5052 with a Titanium alloy (Ti-6Al-4V) which has a higher Young's modulus. This way, you are able to reduce the thickness to 2 mm without reducing the bending stiffness of the beam. Name **at least 2 issues** you might encounter in creating a beam with the outer dimensions shown in Fig. 4 using the same stamping and bending setup?

c) Die-casting.

i) Estimate the **cooling time** to die-cast a part following the dimensions shown in Fig. 4. Assume a coefficient of C = 80 s/mm.

i) After manufacturing the tool by die-casting aluminum 5052, you found that the bending stiffness is insufficient and discovered that the material is quite porous. Qualitatively (no need to make any calculations), list **2 possible causes for porosity and ways to address them.**

i) Even after successfully addressing the porosity issue, the **stiffness of the beam is still inadequate**. Since the die-casting mold was expensive to make, you **do not wish to change the geometry** of the part. Instead, you thought of **changing the material to stainless steel** which has a much higher Young's modulus. List **2 potential issues** that may arise, in terms of **mechanical performance and die-casting** of the bond arm, from implementing this change.

Problem 3 - Layered manufacturing (16 points)

Your manager tasked you to come up with the next-generation bond arm with better dynamic performance than the current aluminum version. You consider using advanced materials including carbon fiber reinforced polymers and additive manufacturing with carbon fiber fillers.

a) **Carbon Fiber Reinforced Polymer (CFRP)**. You decide to design the bond arm using carbon fiber composites, and are considering the geometry, fiber orientation, and expected performance benefit.

   i) **Geometry.** Would you keep a similar geometry to the aluminum bond arm, such as the H-beam (Fig. 3) or U-beam (Fig. 4)? Consider the shape and construction of carbon fiber sheets where they are commonly used (sports equipment and aerospace) and suggest a suitable geometry.

   ii) **Performance gain.** What properties of CFRPs make them desirable alternatives to Aluminum and how would they improve the performance of high-speed precision assembly machines?

b) Additive manufacturing.

i) Comparing the density and Young's modulus of CFRP vs 3D printing (FFF/FDM) nylon with carbon fiber fillers in Appendix 1 and recalling what you know about the FFF process, what can you determine about the **carbon fiber volume fraction** and **fiber length** between these two materials? *Assume that epoxy and nylon has similar densities, while carbon fiber has a significantly higher density than these matrix materials.*

ii) **Competitive advantage.** Considering the lower Young's modulus of 3D printing nylon when compared with CFRP and aluminum, additive manufacturing still has its merits. State and discuss at least **two benefits of additive manufacturing** to produce **bond arms for different machines** with different loads, actuator specifications, and dynamic requirements.

Appendix 1: Physical properties of several metal alloys

Property	AL-5052	Ti-6Al-4V	Stainless Steel 304	Carbon Fiber Epoxy Comp. (Quasi-isotropic)	3D printing nylon with carbon fiber fillers
Density (kg/m^3)	2,700	4,430	8,000	1,600	1,300
Young's modulus (MPa)	70,000	114,000	200,000	60,000	12,000
Yield Strength (MPa)	190	1,100	215	600	80
Ultimate Tensile Strength (MPa)	230	1,170	505	Brittle failure	90
Melting point (deg C)	600	1600	1400	Epoxy degrades at 300	240