MIT 2.008 Design and Manufacturing II

Spring 2025
March 19th, 2025

- All work for CREDIT must be completed in this quiz document
- Closed Book, but you are allowed one double-sided 8.5" x 11" notes sheet
- Calculators are allowed, and we have provided them in the room.
- We have provided the following parts to inspect:
  - 2 lego bricks for questions 2-5
  - 1 metallic cribbage piece for question 6.
- We have provided a caliper to measure relevant dimensions of the parts, as needed. Due to the limited resolution, please report all measurements in **millimeters (mm)** and **NOT inches**.
- Please return the calculator, parts, and caliper at the end of the quiz.

General Notes

- *For qualitative answers, we're not looking for long essays. Please answer using short (1-2 sentence 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: ____________________________

Problem 1		Out of 12 points
Problem 2		Out of 30 points
Problem 3		Out of 15 points
Problem 4		Out of 29 points
Problem 5		Out of 14 points
Total		**100 points**

Problem 1 - Short questions (12 points)

1 point for each correct answer.

For the following prompts, **circle the correct choice** in the brackets, or cross out the incorrect choice(s).

a. To increase the thermoforming production rate, you can use a **(thin/thick)** plastic sheet with **(low/high)** heat capacity, **(low/high)** glass-transition temperature, and **(low/high)** absorptivity of the heater lamp.

b. Circle the joining process(es) below that add(s) another entity (part or material) at the joint, in addition to the parts that are being joined:

   i. **Adhesive joining**

   ii. **Brazing**

   iii. **Soldering**

   iv. **Ultrasonic welding**

c. For a given specification, the following characteristics **increase** the chance that both control limits **(UCL and LCL) fall within the specification limits**:

   i) A process mean that is (**lower than/higher than/centered in between/off-centered from**) the USL and LSL
   ii) A process variation that is **(low/no effect/high)**
   iii) A sample size that is **(low/no effect/high)**
   iv) A process capability that is **(low/no effect/high)**

For Problems 2-4, you are provided with 2 large "DUPLO" LEGO bricks (1 red and 1 blue). In the following problems, you will analyze the considerations of manufacturing, quality control, and assembly. While working through the questions, you would need to **measure the relevant dimensions using the calipers** provided. You may also refer to Appendix 1 for some formulae.

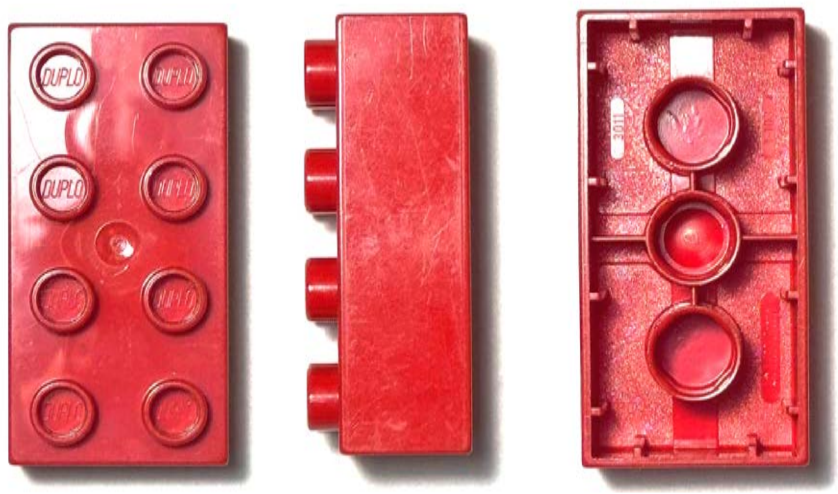


Figure 1 - Photographs of the DUPLO LEGO brick

The LEGO brick is made out of ABS which has the following material properties. For your convenience, the same table is shown in Appendix 2 in case you want to tear it off and use for reference.

Property	**Value**
Density	ρ = 1100 kg/m^3
Specific heat capacity (plastic)	c_p = 1700 J/kg-K
Thermal conductivity	k = 0.2 W/m-K
Glass transition temperature	T_g = 105°C
Melt temperature	T_m = 220°C
Viscosity of Molten ABS (@ 220 °C)	350 Pa•s
Elastic Modulus	2 GPa
Static Friction Coefficient	0.1

Problem 2 - Injection Molding (25 points)

a. Specify (and **mark on Fig. 1** where applicable) 3 features that indicate that the part was manufactured by injection molding, instead of thermoforming **(3 points)**

b. In terms of the injection molding process, **(5 points)**

   i. Calculate the **flow path ratio.** Assume uniform thickness in the whole part

   ii. What kind of **defect** is likely to occur if the part is molded using standard injection molding process parameters?

   iii. Suggest **two changes** to the injection molding process parameters that can be implemented to reduce the chance of this defect.

c. The ABS material is injected to fill the injection mold cavity to create the part in 1 second. Calculate the required **injection pressure** at the gate. **(4 points)**

d. Calculate the **clamping force** required for a single LEGO brick **(4 points)**

e. The injection molding machine has a rated clamping force of 45 kN. **(4 points)**

   i. What's the maximum **number of bricks** that can be reliably injection-molded together **in a single mold**?

   ii. Sketch the ideal **arrangement of the parts in the multi-cavity mold** to ensure uniform injection pressure at all the gates.

f. Estimate the **cooling time** for the brick, assuming that the following condition is met: $(T_{melt} - T_{mold}) \approx 10\,(T_{ejection} - T_{mold})$ **(4 points)**

g. Regular-sized LEGO bricks are smaller than these DUPLO LEGO bricks.

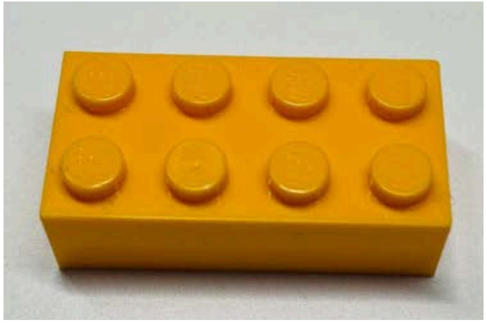


Figure 2 - Photograph of a regular-size LEGO brick.

Say that the regular-sized bricks are exactly **half the size of these DUPLO bricks in all dimensions: length, width, height, and wall thickness.** Assuming the same material and mold-filling time, estimate the ratio of the following parameters (e.g. 0.5x, 2x, etc.) to produce regular-sized bricks when compared to the DUPLO bricks: **(3 points)**

i. injection pressure at the gate

ii. clamping force per part

iii. cooling time

Problem 3 - Thermoforming (15 points)

DUPLO and regular LEGO bricks do not fit with each other. However, both of them fit on the LEGO "grass" base plate, as shown in the image below!

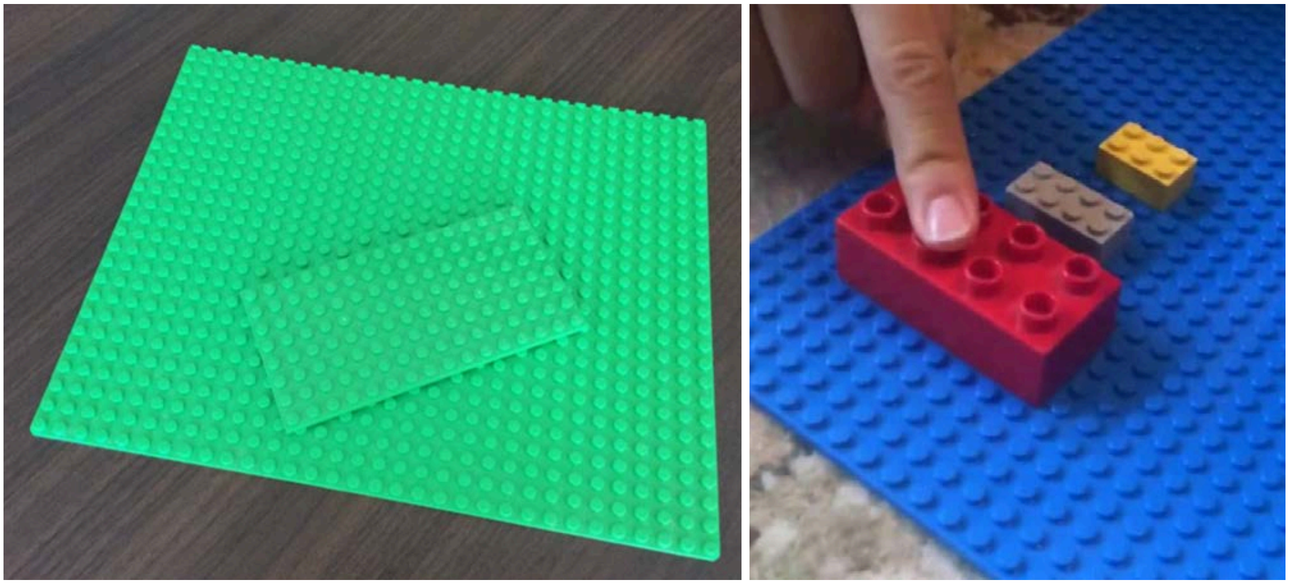
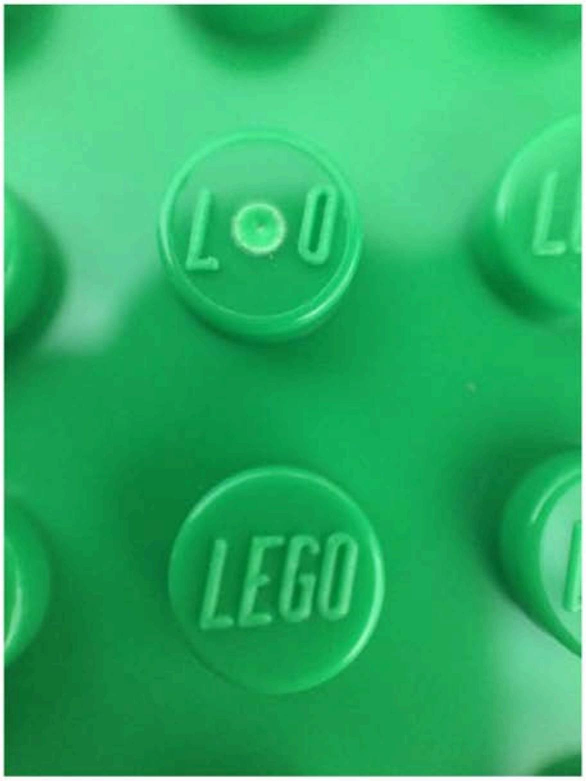
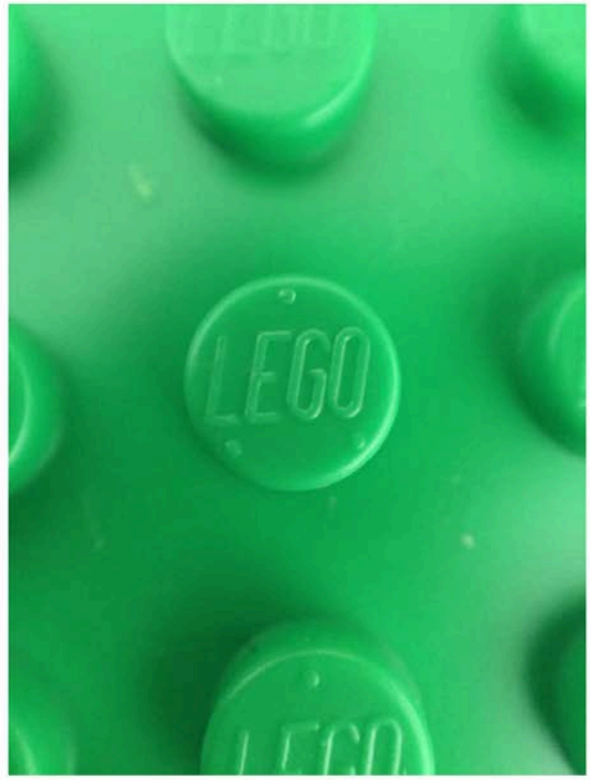


Figure 3 - LEGO base plates (left), DUPLO and regular bricks are compatible with the base plate (right)

a. Have you ever noticed that smaller base plates are quite rigid, whereas the larger base plates are flexible? Now that you've taken 2.008, you can appreciate that they are made with two different processes: injection molding and thermoforming! Just using your knowledge of these two processes, which process do you think is used to make the large flexible base plate? Give **two reasons** why this process is used instead of the other process? **(3 points)**

b. Let's inspect the two kinds of base plate in more detail. From the magnified top face shown below, **identify and label the process used** to make each of the two parts. Give **one identifier for each** that led to your choice **(3 points)**





Injection Molding / Thermoforming

Reason or identifier:

Injection Molding / Thermoforming

Reason or identifier:

c. Now we shall further inspect the cross-section of the two base plates, as shown below. **(7 points)**

   i. Similar to question (b), identify which process is used for each picture. Give **one reason each** for choosing that process.

   ii. On the cross-section of the part that you believe to be thermoformed, **sketch the thermoforming tooling** around it. Indicate the key features in the tooling necessary for thermoforming the part, based on what you observe about this geometry (while working on this question or the questions above).

Injection Molding / Thermoforming

One reason or indicator:

Sketch the thermoforming tooling around the cross-section that was thermoformed

Injection Molding / Thermoforming

One reason or indicator:

d. Can the DUPLO **bricks you have also be thermoformed**? Justify why or why not. **(2 points)**

Problem 4 - Process Control and Assembly (19 points)

Arguably the two most important features on a LEGO brick are the "stud" (positive boss, shown as green circle on the red brick in Fig. 4) and the "anti-stud" (cavity, shown as a yellow circle on the blue brick in Fig. 4) as they directly influence how bricks fit with each other. Hence, it is crucial to keep these features within the specification. *For simplicity, we define the geometry of the anti-stud as a circle that the stud fits inside of.*

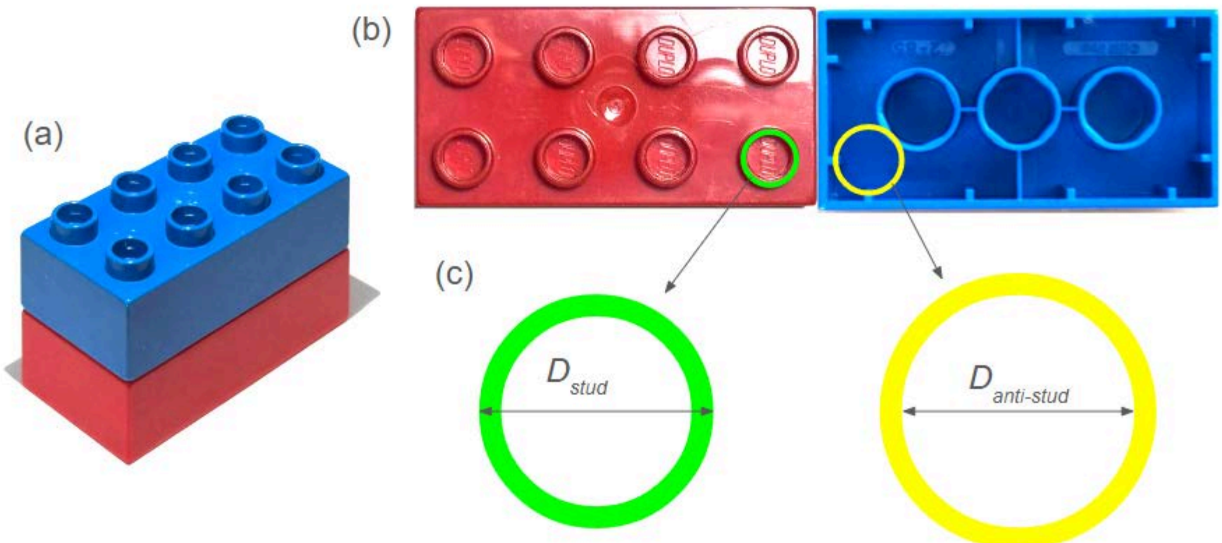


Figure 4 – (a) Two bricks assembled together. (b) Top and bottom views of the bricks showing the stud (green circle on red brick) and anti-stud (yellow circle on blue brick). (c) Enlarged circles indicating the stud outer diameter (D_{stud}) and anti-stud inner diameter ($D_{anti\text{-}stud}$)

The **stud outer diameter** has a specification of **D_{stud} = 9.2 mm +0.03/+0.05 mm**, while the **anti-stud inner diameter** has a specification of **$D_{anti\text{-}stud}$ = 9.2 mm -0.05/-0.03 mm**.

a. Explain how these nominal diameter and tolerance values ensure that two bricks that meet the specifications will stay together when they are assembled. **(2 points)**

For questions b-g, we will focus on the dimension of the **stud outer diameter** which has a specification of **D_{stud} = 9.2 mm +0.03/+0.05 mm**

b. What are the USL and LSL of the **stud outer diameter**? **(2 points)**

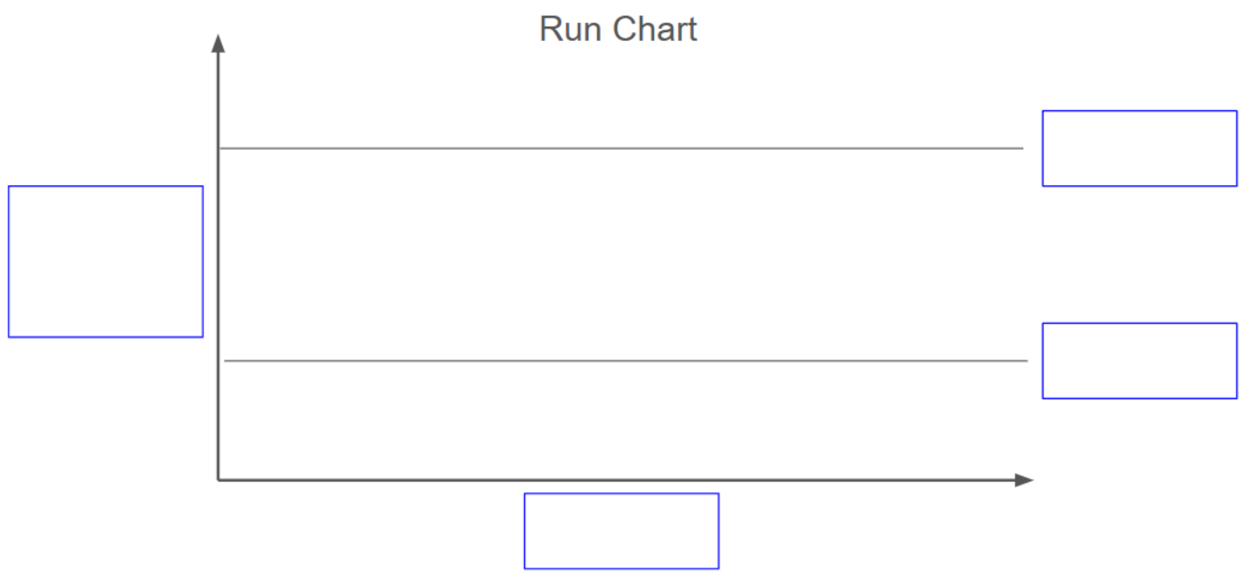
c. LEGO's injection molding subcontractor claims that their **process** can create bricks with the **stud outer diameter** dimensions having a $C_p = C_{pk} = 1.33$. **(6 points)**

   i. What does the fact that $C_p = C_{pk}$ say about the process distribution curve relative to the specification limits?

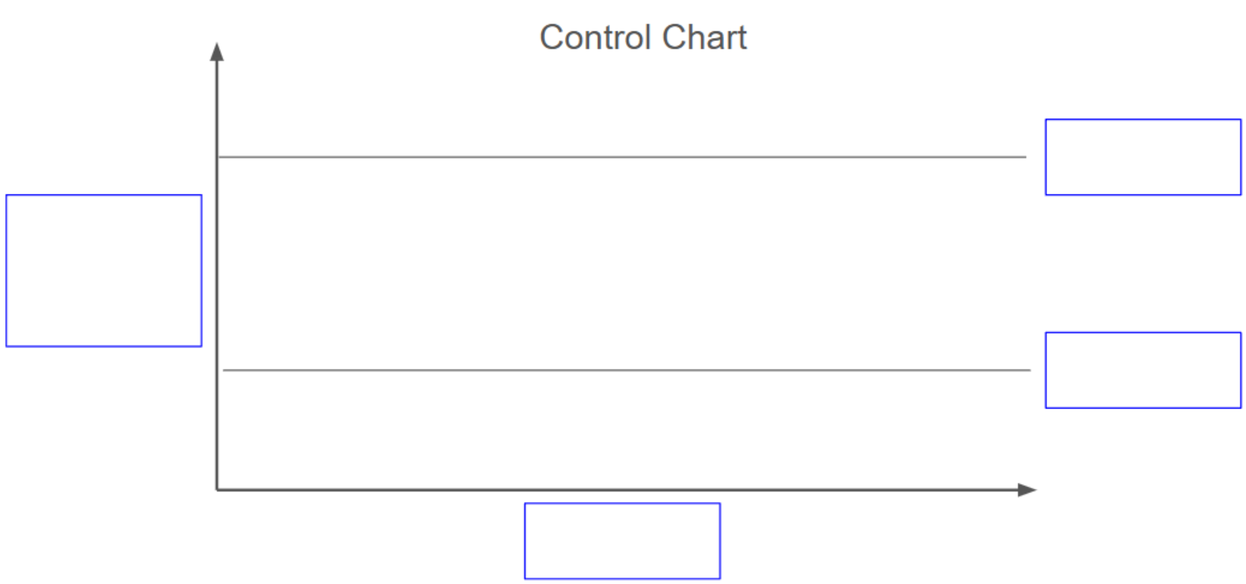
   ii. Calculate the process mean and standard deviation of the stud outer diameter.

d. For statistical process control, 9 parts are sampled for every 1000 bricks molded. Calculate the appropriate **upper and lower control limits (UCL and LCL)** for the stud outer diameter using the process described above. **(4 points)**

e. You are preparing to plot a run chart of this process. Please **label the axes and limits** inside the blue boxes in the run chart below. Ignore the fact that there are no data points in the chart. **(4 points)**



f. Separately, you are also preparing to plot a control chart. Please **label the axes and limits** inside the blue boxes in the control chart below. Ignore the fact that there are no data points in the chart. **(4 points)**



g. What would realistically happen to the fit of the LEGO bricks and the force needed to assemble and disassemble them if **the stud outer diameter is**: **(3 points)**

    i. **Smaller** than the specification

    ii. **Slightly larger** than the specification

    iii. **Much larger** than the specification

h. For a given feature dimension within the specifications, how would the force needed to assemble and disassemble the LEGO bricks be affected by the following changes to the injection molding process: **(4 points)**

    i. Molding the LEGO with a **different material**

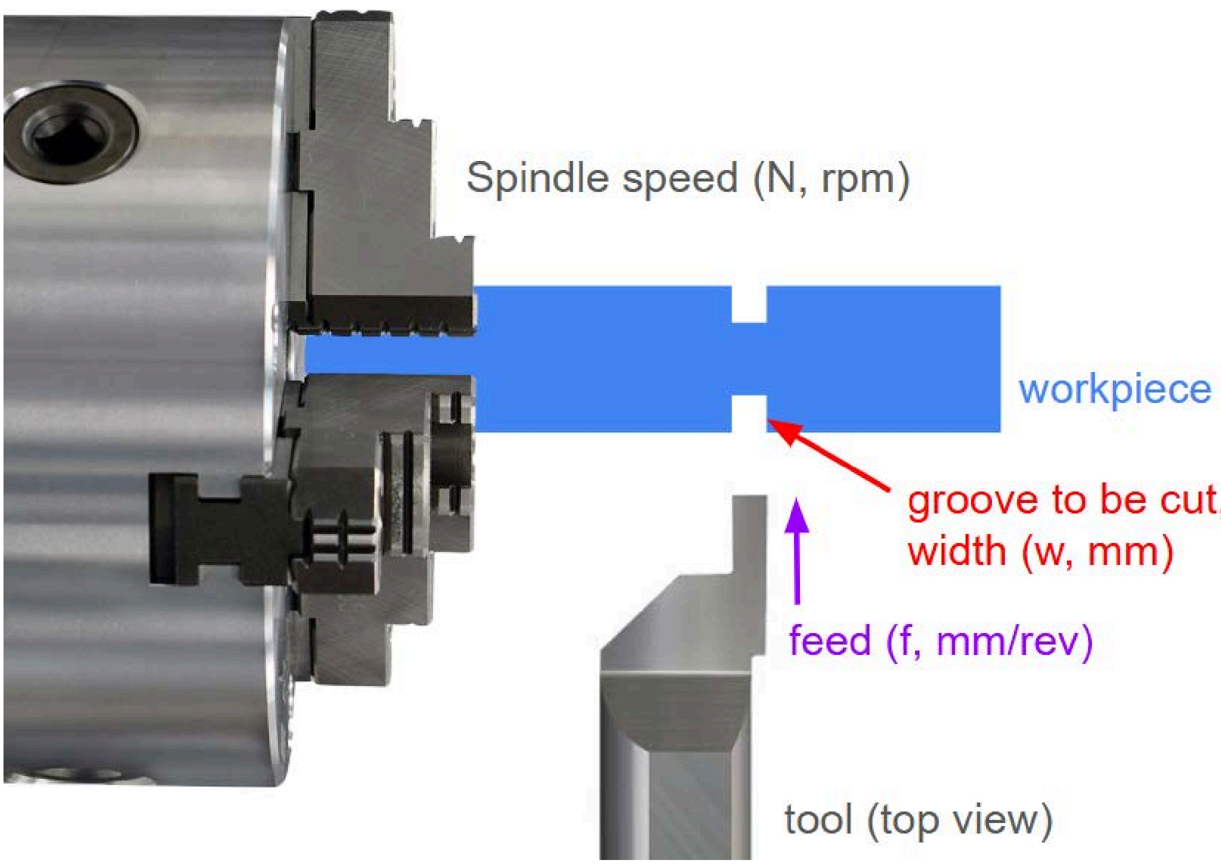
    ii. **Polishing the mold** to achieve a smoother molding surface

Problem 5 - Cutting (14 points)

Figure 5 – Photograph of an aluminum cribbage piece (the color is not indicative of the bulk material).

You want to **cut a single groove** in the aluminum cribbage piece. Instead of a regular lathe that has a wide cutting edge and feeds in the axial direction, you are using a custom lathe that has:

- a cutting tool edge width equal to the width of the groove.
- feeds in the radial direction**.**



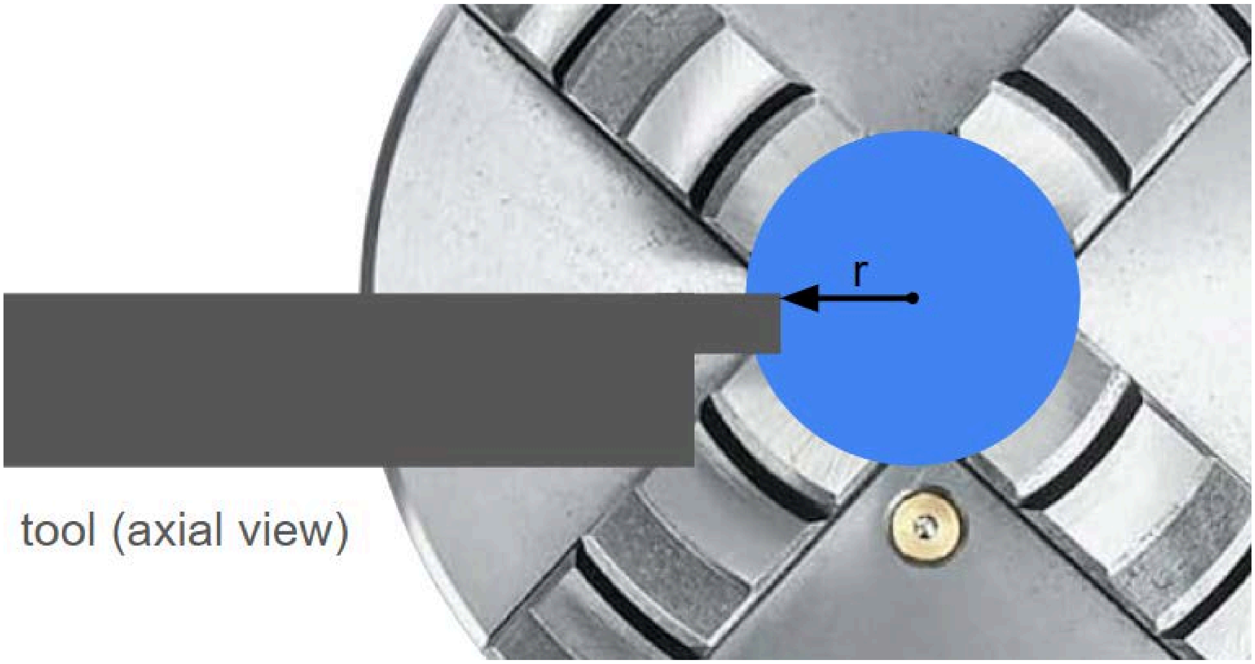


Figure 6 – Top-down (top image) and down-the-axis (bottom image) diagrams showing the cutting of the groove of cribbage piece on the lathe tool

a. During the lecture, we provided an equation for average MRR based on the average diameter of the part during the turning process. Now, we want to formulate the instantaneous MRR equation as a function of the current workpiece radius (r) at the region being cut. Using the variables defined in the figures above, write the equation for **MRR(r)**. The answer should be in variables r, other variables listed in the figure (N, f, w), whichever are relevant, and constants. **(6 points)**

b. At what point during the cutting operation will the machine need to output the highest power? **(2 points)**

c. Given the cutting parameters below, calculate this **highest output power**. (Measure the cribbage dimensions as needed). Would this stall the lathe at LMP? **(4 points)**

Spindle speed (N) = 2500 RPM
Feed (f) = 0.5 mm/rev
Aluminum Specific cutting energy (u_s) = 0.7 W.s/mm^3

d. Assume you are not going to stall the machine. Calculate the cutting force. **(2 points)**

Appendix 1. Formulae

Injection Pressure

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

μ = viscosity of plastic

t_{fill} = time needed to fill mold

Clamping Force

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

Cooling Time

$t_{cool} \approx \frac{h^2}{4\alpha}$ with $\alpha = \frac{k}{\rho\, c_p}$ if the following is satisfied: $(T_{melt} - T_{mold}) \approx 10\,(T_{ejection} - T_{mold})$

α = thermal diffusivity

k = thermal conductivity

c_p = specific heat capacity

ρ = density

h = characteristic part thickness

<u>Appendix 2: Physical properties of ABS used in the injection-molding of the LEGO DUPLO brick.</u>

Property	**Value**
Density	$\rho = 1100\ kg/m^3$
Specific heat capacity (plastic)	$c_p = 1700$ J/kg-K
Thermal conductivity	k = 0.2 W/m-K
Glass transition temperature	$T_g = 105^oC$
Melt temperature	$T_m = 220^oC$
Viscosity of Molten ABS (@ 220 ^{o}C)	350 Pa•s
Elastic Modulus	2 GPa
Static friction coefficient	0.1