Spring Semester 2025
Microengineering Section (MT)
Bachelor Semester 6 (BA6)

MICRO-301

Manufacturing Technologies

Exercises Booklet

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Revised, redesigned, and expanded edition.

École polytechnique fédérale de Lausanne

Exercises

1. Using Ashby Plots

Let us consider a beam with square cross-section of area A.

1. What *material properties* should we optimize to minimize the mass of a beam of length L and achieve the maximum stiffness in bending? Follow the method provided below (Steps 1-3).
2. Which material would you select considering this problem? We will assume as requirements that the minimum value for the modulus should be $1\ \mathrm{GPa}$ and that the material should have a density higher than $0.3\ \mathrm{Mg/m^3}$ (or $300\ \mathrm{kg/m^3}$). Follow Step 4.

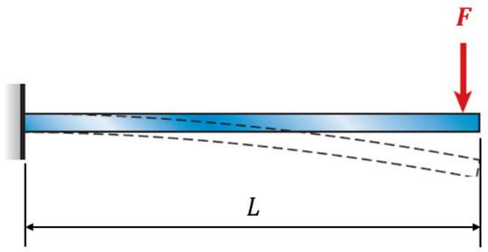

Figure 1. *Beam submitted to a point load at the tip.*

Method.

- **Step 1:** translate the question into a set of equations (express the requirements as simple equations).
- **Step 2:** identify design parameters versus material properties and eliminate free variables to define an objective function.
- **Step 3:** formulate the optimization problem to visualize it as a line on an Ashby plot.
- **Step 4:** choose the relevant Ashby plot and draw the line to define which materials would be suitable among the various possibilities.

You may find the following plots useful during the semester! You can easily find more on Internet.

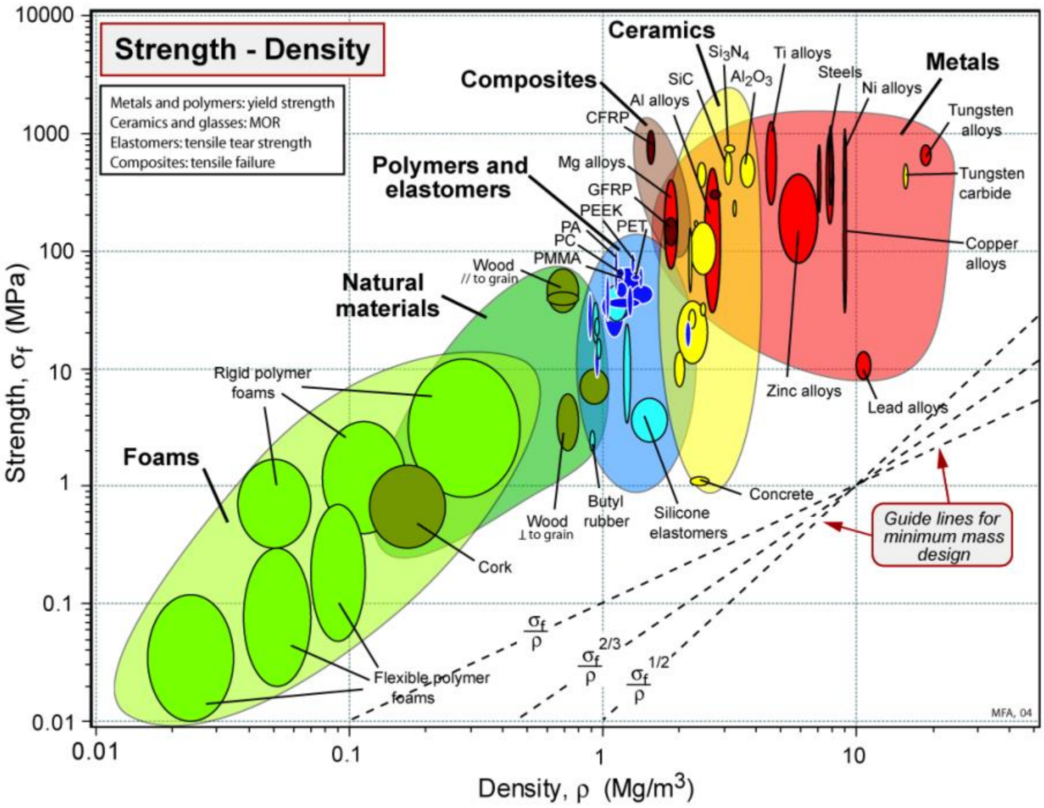

Figure 2. *Ashby plot #1.*

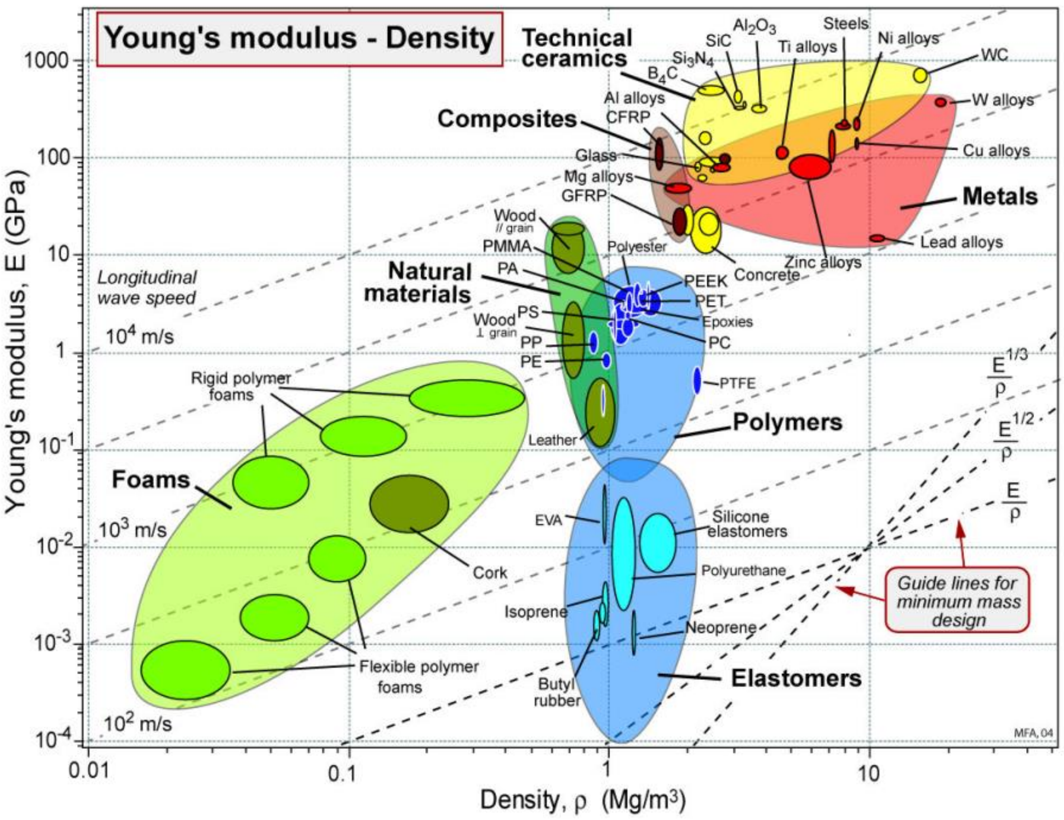

Figure 3. *Ashby plot #2.*

2. Surface Wettability

In this exercise, we explore the importance of wettability in the behaviour of surfaces. Specifically, we study the problem of capillary rise. This problem is common in manufacturing and arises in various situations, like for dispensing adhesive, ink-jetting, packaging, self-alignment in electronic circuits during soldering or gluing, etc.

2.1. Qualitative Analysis

We consider the system shown in **Figure 4**.

1. Describe the difference between red and blue capillaries.
2. Show the balance of forces at the interfaces:
    a. Between a blue capillary and the liquid
    b. Between a red capillary and the liquid
3. Discuss the phenomenon of capillary rise and its opposite effect. What makes a liquid climbing up a capillary or sinking down?

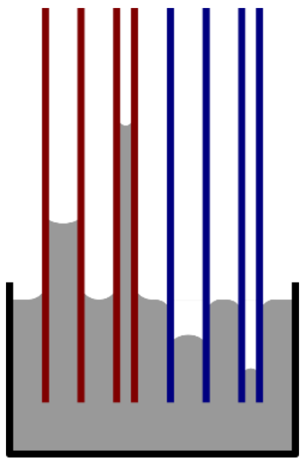

Figure 4. *Bucket containing a liquid (shown in grey) with a set of capillaries (thin tubes) partially immersed in the liquid.*

2.2. Quantitative Analysis

We consider the case of a single red capillary as described in the previous part. We assume that the system is in equilibrium and the liquid in the capillary has now reached a height h.

4. In the case of **Figure 5**, is the inner surface of the capillary, hydrophobic or hydrophilic? Justify your answer.
5. Using the balance of forces, express the height h that the liquid will reach as a function of the surface tension and the density of the liquid.
   Hint. Analyse the balance of forces acting on the liquid meniscus (pressure and capillary force). Start by finding an expression for F_{cap} based on a dimensional analysis.
6. Repeat Question 5, but this time using Laplace equation as seen in Lecture 2. Show that this approach yields an equivalent result as found in the previous question.
7. *Discussion from the viewpoint of designing an element.* Describe for a given surface tension how one can reach the maximum capillary rise. What parameters can be optimized?

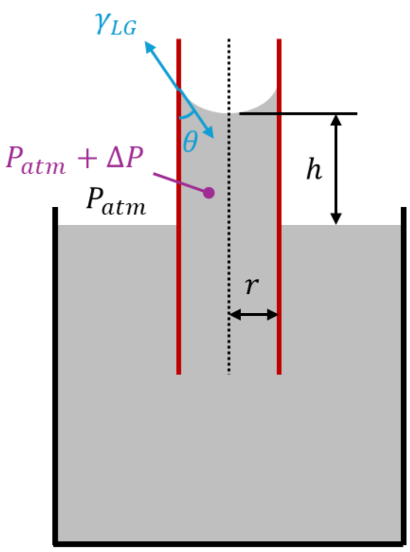

Figure 5. *Analysis of a single capillary. We assume that the meniscus has a radius r. Other relevant parameters are shown in the drawing.*

3. Surface Analysis

Using the open-source software Gwyddion, we aim at analysing atomic force microscope (AFM) images of the surface of a fused silica specimen, exposed to a laser beam and subsequently etched in hydrofluoric (HF) acid. Such studies are usually done to understand how roughness may be correlated to functional properties. In this particular case, it was used to understand a change in mechanical strength of manufactured flexures.

Three images are provided, each one corresponding to a different chemical etching duration.

The learning objectives of this exercise are to:

i. Get familiar with surface analysis tools,
ii. Separate and identify waviness and roughness components that are part of the surface texture,
iii. Discuss the links with the manufacturing processes that have been used.

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1. Choose an image. Describe it in two and three dimensions. Describe features and identify, if needed, defects and artifacts that may be present in the image.
2. Analyse the surface with the *Roughness* command. Discuss the differences between texture, waviness, and roughness.
3. Separate waviness and roughness components by using FFT filtering. We recommend starting with 1D-filtering, to have an understanding of the working principle of a FFT filter, then proceed with 2D-filtering for better precision. Learn how to add/subtract the different contributions. Plot the results in 2D and in 3D.
4. Compare the plots obtained in Question 3 with the profiles investigated in Question 2. Are the profiles of waviness and roughness similar? Why?
5. Repeat questions 1 to 4 with different images to study the effect of the etching parameters on the surface texture. Do you notice particular surface textures with preferred orientation?

4. Bennett and Porteus Model for Reflectivity

During and after manufacturing, polishing requirements must be carefully considered depending on the function that a surface shall fulfil. *Optical surfaces* typically have stringent requirements in terms of surface roughness, at the price of a certain cost. In general, the lower the roughness, the higher the cost.

To investigate this problem, we analyze the Bennett and Porteus model seen in class:

$$R_s(R_q) = R_0\left(1 - e^{-\left[4\pi\left(\frac{R_q}{\lambda}\right)\cos(\theta_i)\right]^2}\right)$$

where R_s is the total scattered intensity, R_0 the intrinsic reflectance of the surface (i.e., that of a perfectly smooth surface of the same material), R_q the RMS roughness of the considered surface, λ the incident wavelength and θ_i the angle of incidence of light (defined with respect to the normal to the surface, as shown in **Figure 6**).

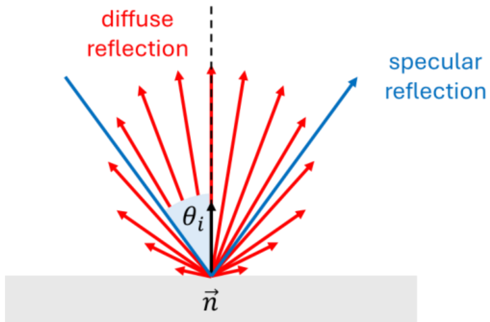


Figure 6. *Representation of the light interaction with a rough surface.*

4.1. Mirror Surface

1. We would like to produce a 'good' mirror surface, that is, as least as possible visible. How should we optimize the ratio between the scattered and intrinsic reflectance?
2. Using your favourite plotting program (Matlab or others), plot a normalized, dimension-free representation of the scattered intensity for various angles (i.e., the ratio R_q/λ versus R_s/R_0).
3. Discuss the influence of the angle of incidence of a light beam on the scattered intensity.
4. Let us assume now that the angle of incidence is $\pi/4$. What should be the roughness to achieve a maximum of 10% scattered intensity for a wavelength of (a) $10\ \mu\text{m}$? (b) $0.5\ \mu\text{m}$? (c) $0.2\ \mu\text{m}$? *Note. This is the typical wavelength of CO_2 lasers, widely used in laser cutting applications.*
5. Consider the tables providing the arithmetical roughness R_a for various types of processes (see Lecture 2, slides 26-27). Which process(es) could be considered to achieve the scenarios discussed in (a) Question 4(a)? (b) Question 4(b)? (c) Question 4(c)?
6. What angle could we choose to make the surface as reflecting as possible and to minimize the scattered intensity?

4.2. Measurement of the Surface Roughness

7. Now, we would like to perform a surface roughness characterization by measuring the reflectivity properties of a given surface. For this purpose:
   a. What figure of merit should you measure?
   b. What angle θ_i should the incident light have?
   c. Would you prefer an incident light with longer or shorter wavelengths?
8. Express R, the specular reflectance of the rough surface at normal incidence.
9. Starting from the expression for R found in the previous question and assuming that $R/R_0 \to 1$, derive an expression for the RMS roughness of the surface as a function of R and R_0.
10. Finally, give an expression for the total diffuse reflectance and interpret the result.

5. Gaussian Beam Propagation

In this exercise, we simulate the propagation of Gaussian beams and the influence of their main parameters.

1. Install the GaussianBeam software.
    a. Initiate an *ideal* Gaussian beam with a wavelength of $\lambda = 600\ \mathrm{nm}$ (orange), a beam diameter of $D = 250\ \mu\mathrm{m}$ and a beam quality factor $M^2 = 1$.
    b. We are given lenses with focal lengths $f = 100\ \mathrm{mm}$, $50\ \mathrm{mm}$, $20\ \mathrm{mm}$, and $10\ \mathrm{mm}$. Based on your prior knowledge, how should the waist diameter evolve as a function of these focal lengths?
    c. Check your assumptions using the software and conclude.
2. Change the initial beam diameter to $D = 500\ \mu\mathrm{m}$, what do you observe? Determine the waist diameters in this case for each of the lenses mentioned above.
3. How does the beam waist compare to the numerical aperture of a given objective?
4. Now, set a beam diameter of $D = 250\ \mu\mathrm{m}$ and a lens with a focal length $f = 20\ \mathrm{mm}$. Observe the evolution of the beam propagation as a function of the following wavelengths: $600\ \mathrm{nm}$, $300\ \mathrm{nm}$ (UV-B), and $9999\ \mathrm{nm}$ (LW-IR). What do you conclude?
5. Keeping the same conditions as for Question 4, with a wavelength of $600\ \mathrm{nm}$, initiate a *real* Gaussian beam (that is, *non-ideal*). What do you observe?
   Hint. Which parameter should you change to describe a realistic Gaussian beam?

6. Material Removal Rate in Laser Processing

We consider a pulsed laser. The pulses are emitted at a frequency f. This frequency is commonly called *repetition rate*. Furthermore, we assume that the laser at focus has a spot radius of w_0, and each single pulse carries an energy E_p. Finally, we assume that the ablation depth *per pulse* is z_a.

1. How would you define the *material removal rate* in the case of an ablation process? Give an expression for this MRR.
   Note. In the jargon of laser processing, the material removal rate is referred to as ablation rate.
2. How would you define the *MRR energy efficiency* (i.e., "how much volume of material per spent unit of energy is removed")? Give an expression for this MRR_E.

Application. Let us consider the case of cutting a polymer (ABS) with a UV laser. We provide the following parameters: $MRR_E = 0.067\ \mathrm{mm^3/J}$, $f = 30\ \mathrm{kHz}$, scanning speed $v = 10\ \mathrm{mm}/s$, average optical power $P = 20\ \mathrm{mW}$, and $2w_0 = 11\ \mathrm{\mu m}$, the spot diameter. We assume that the spot diameter stays constant over the thickness of the considered material.

3. Calculate the ablation rate per pulse and the ablation rate.
4. How long would it take to cut a $c = 1\ \mathrm{mm}$ square out of a $t = 200\ \mathrm{\mu m}$ thick substrate?

7. Glass Manufacturing with Femtosecond Lasers

(by Antoine Duret)

7.1. Femtosecond Laser Printing

Femtosecond laser processing combined with chemical etching is a straightforward two-step process described in the figure below.

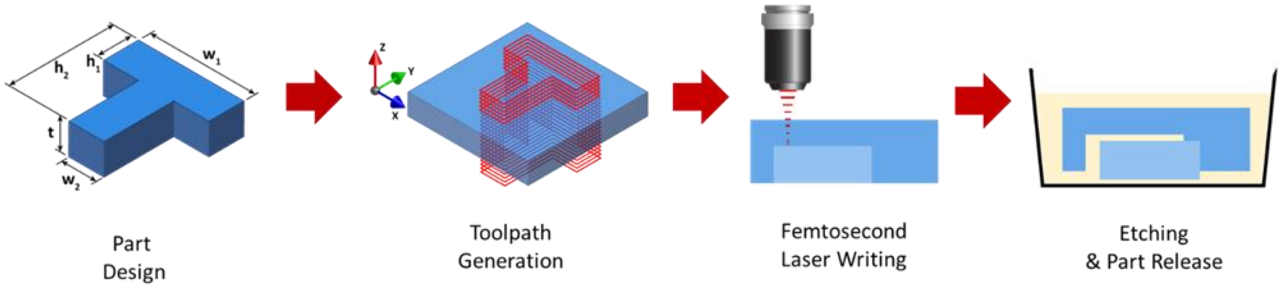


Figure 7. *In the first step, after creating a beam path that defines the contour of the part, the raw material is exposed to low energy laser pulses. There is no ablation, but the inner structure of the material is modified. In the second step, the exposed patterns are detached by immersing the glass specimen in an etching bath.*

After going through the usual part design on a CAD software, a "toolpath", here the trajectory of the laser beam, is generated via a discretization software. The first step is then the femtosecond laser writing of bulk material along the generated toolpath. As seen in class, because of the brevity of the interaction involving extreme peak-power, a special laser-matter interaction is taking place, and the material is locally transformed due to non-linear absorption.

When the toolpath is completely exposed, the glass slide is dipped in an etching solution. During this second step, the acid etches the written areas up to a thousand times faster than the unwritten one (so-called "pristine" glass), slowly removing the desired material and detaching the part.

1. List the benefits and drawbacks of such a process in comparison to other laser-based manufacturing technologies.
2. Glass appears as an ideal material because of its transparency at $1030\ \mathrm{nm}$, the wavelength of the femtosecond laser. List other reasons making it very relevant for microengineering applications.
3. What glass property may act as a troublemaker if the process is not well controlled?
4. The femtosecond laser pulses induce a change of volume in the matter. What are the three consequences resulting from this volume change? Why are they important?
   Hint. Consider one mechanical consequence, one optical consequence and one process-related consequence.

7.2. Case Study of a Glass Package

Consider the part shown in the figure below. It is a $t = 5.8$ mm thick package. The design is ready, but you need to define the toolpaths required to manufacture the part.

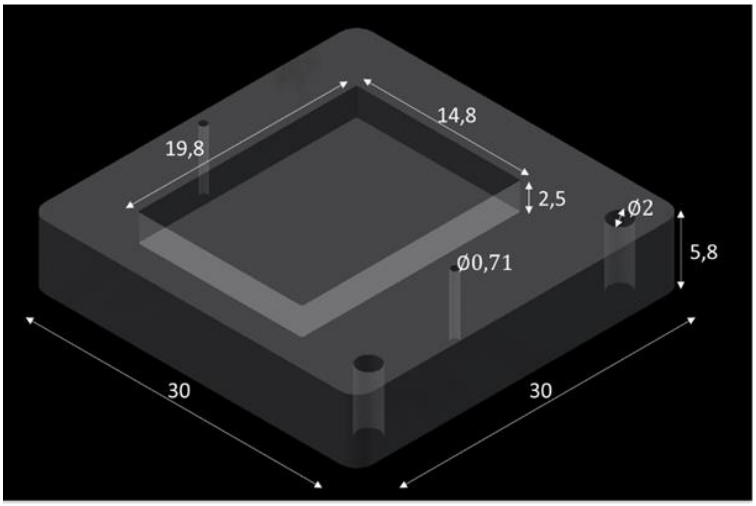


Figure 8. *CAD model of a glass package with features' dimensions.*

5. Knowing that the laser beam comes from the bottom, explain how you would proceed to write the geometry in a glass slide of desired thickness.
6. Knowing that the vertical pitch is $p_v = 15$ μm, how many laser passes do you have along the full height of the part?
7. Femtosecond lasers have very specific parameters. In our case, knowing that the laser has a repetition rate $RR = 1000$ kHz, a peak power $P_{peak} = 1.53$ MW and a pulse duration $PD = 150$ fs, compute the average power P_{av} of the light source.

7.3. Selectivity in Etching

Laser modified regions exhibit enhanced etching rates. This allows for selective fabrication of complex geometries. Typical selectivity of fused silica in a 45% KOH aqueous solution is $1:115$. The bulk material is etched as well but at a much smaller rate.

In general, the unmodified material is assumed to be etched with a rate of $i = 0.4 - 0.5\ \mu m \cdot h^{-1}$, while the written material has a rate equal to $w = 350 - 500\ \mu m \cdot h^{-1}$. Therefore, the need for design compensations to counteract etching on the unmodified material will depend on the critical etched length l_c in the part.

In the following, always consider the worst case for these etching rates.

8. What is the minimum etching time $t_{etch,min}$ required for our package?
9. What is the maximum parasitic etching d_p in that case?
10. Detail two strategies to minimize this parasitic effect and reach dimensions closer to the expected ones.
11. Evaluate the verticality of the traversing holes.
12. Empirical data show that the etching time typically improves the failure strength, allowing some parts to withstand stresses more than 2 GPa above the theoretical yield strength of glass. Can you explain why?

7.4. Welding the Package

We consider the case where we would like to laser-weld two parts together as illustrated below.

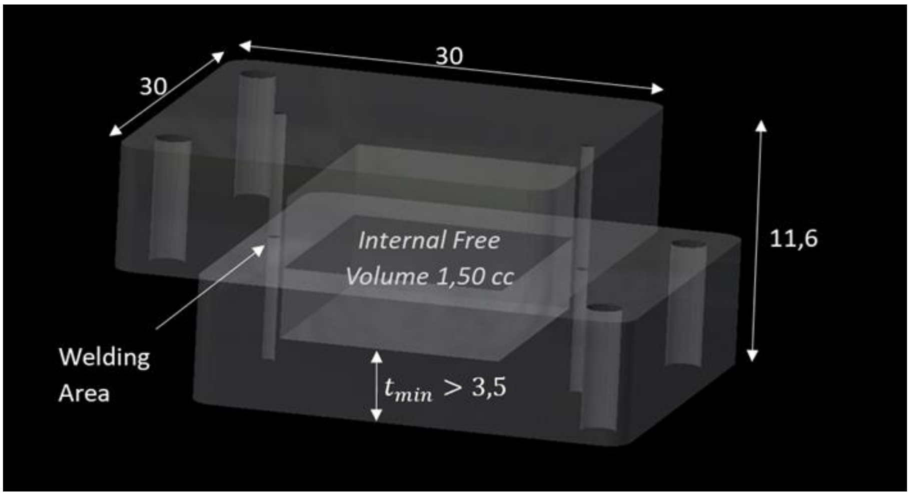


Figure 9. *CAD model of the welded package.*

13. *(Advanced)* Think about what could go wrong with the package studied in this exercise, knowing that we would like to flip another identical part on top of the first one and laser-weld them together to form a full package, as shown in **Figure 9**. Think about the stress concentrations and their implications. Once you have identified at least two potential issues, propose some ideas to solve them.

8. Cutting Strategy in Blanking[1]

In this exercise, the objective is to cut circular disks out of a metal strip and to limit the amount of wasted materials.

Two strategies are considered (see **Figure 10**). The first one is to cut a single line of disks out of a strip of metal, while the second one is based on an arrangement of two lines cut from the same strip.

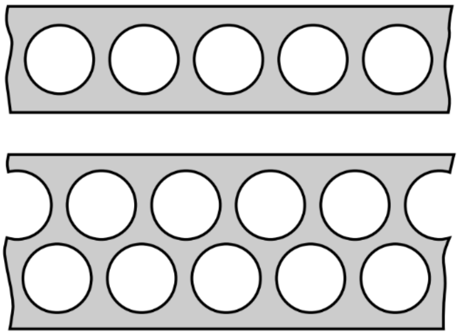


Figure 10. *Cutting disks out of a metal strip. Top: one line of disks per strip; bottom: two lines per strip.*

1. *Qualitative Assessment.* Intuitively, which of the two strategies will yield the lowest amount of scrap metal? What are the limiting factors determining the minimum distance between holes?
2. *Quantitative Assessment.* For both cases, estimate the percent scrap in producing round blanks if the clearance between blanks is one tenth of the radius of the blank (i.e., 10% of the disk radius needs to be preserved during cutting). Conclude.
   Hint. Draw a repeating unit cell.
3. Calculate the blanking force for punching a disk of $5\ mm$ in diameter out of a 0.5 mm-thick strip of spring steel ($\sigma_L = 400\ \text{MPa}$, $\tau_L \approx 0.5\sigma_L$).

[1] *Adapted from Kalpakjian, Schmid,* Manufacturing Processes for Engineering Materials, *6th Edition, Pearson Ed.*

9. Folding

9.1. Preliminary Work

1. Demonstrate the formula shown in class that expresses the strain in a beam curved in pure bending. Assume that the curvature remains big compared to the beam thickness, so that the neutral line is passing exactly through the middle of the beam.
   Hint. Make a proper drawing and use the basic definition of the engineering strain.

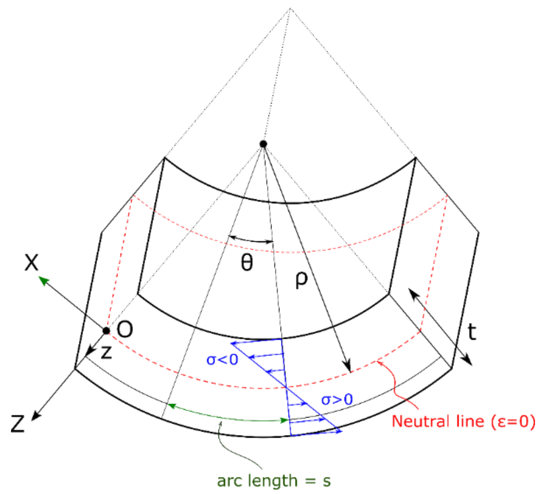


Figure 11. *Loading case illustration. The neutral line is shown and corresponds to the state of zero strain. The upper part is under compressive stress, while the bottom one is in a state of tensile stress.*

9.2. Plastic Deformation[2]

2. We bend the beam. Knowing the plastic stress limit σ_y for a given material, calculate the radius of curvature – we will call it R_p – for which plasticity in the beam will start to appear.
3. Describe how the stress state evolves in the material as the beam is bent beyond R_p. What happens during unloading? Use drawings to illustrate the evolution of the stress state and assume that the deformation remains elastoplastic.

Application. A uniform rectangular beam is subjected to a bending moment $M = 36.8\ \text{kN}\cdot\text{m}$. It is made of an elastoplastic material with $\sigma_y = 240$ MPa and $E = 200$ GPa.

4. Determine the thickness of the elastic core t_Y and the radius of curvature of the neutral surface, knowing that the applied moment and maximum moment for elastic bending are linked as:

$$M = \frac{3}{2} M_Y \left(1 - \frac{1}{3}\frac{y_Y^2}{c^2}\right)$$

5. After unloading the beam (loading reduced back to zero), determine the distribution of residual stresses (draw the correspond graphs) and the radius of curvature of the neutral surface (i.e., at the edge of the elastic core).

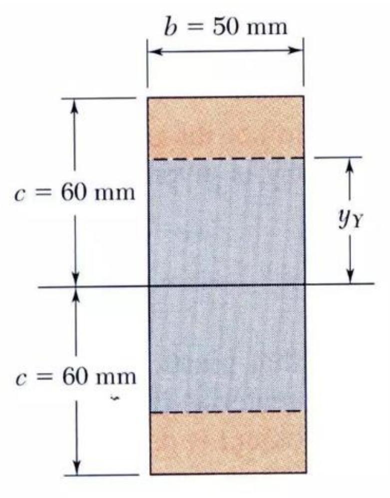


Figure 12. *Illustration of the beam's cross-section and its dimensions.*

[2] *Adapted from Beer, Johnston, DeWolf,* Mechanics of materials, *3rd Ed., The McGraw-Hill Companies.*

9.3. Hinge Forming[3]

A hinge is being formed in a $t = 1.00$ mm thick aluminium sheet by pressing it against a $\varnothing_{die} = 20.0$ mm diameter die, as illustrated in the figure below. We assume that the yield strength for the aluminium beam is $\sigma_{y,Al} = 90$ MPa. Further we assume that the Young's modulus for aluminium is $E_{Al} = 70$ GPa.

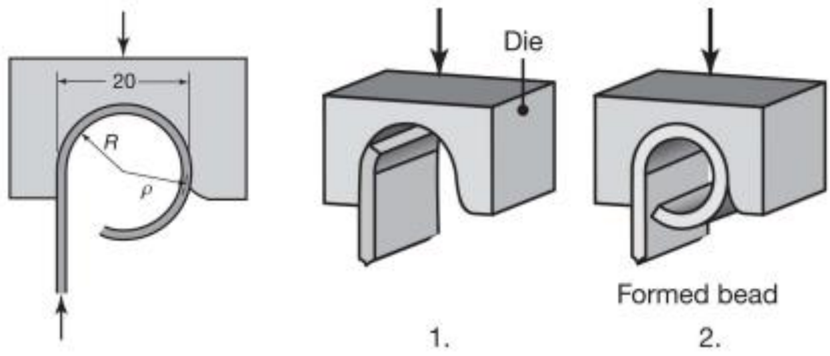
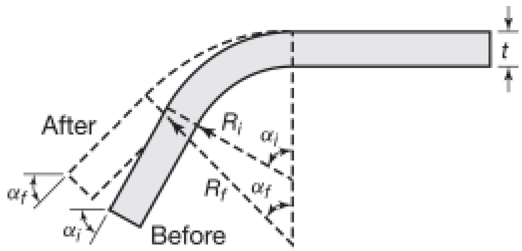


Figure 13. *Forming of a cylindrical hinge by bending an aluminium sheet in a $20 - mm$ die.*

6. Calculate the initial bend radius R_i.
7. Considering the spring back effect, what will be the outside diameter $\varnothing_f$ of the hinge once released from the die?
   Hint. The following formula expresses the final bent radius as a function of the initial bend radius:



$$\frac{R_i}{R_f} = 4\left[\frac{R_i \sigma_y}{Et}\right]^3 - 3\left[\frac{R_i \sigma_y}{Et}\right] + 1$$

8. What is the amount of permanent strain in the final shape? Assume that the bending radius is still enough large compared to the beam thickness so that the neutral line is still in the middle.

[3] *Adapted from Kalpakjian, Schmid,* Manufacturing Processes for Engineering Materials, 6*th Edition, Pearson Ed.*

10. Solidification Time in Casting[4]

A cylinder with a diameter-to-height ratio of 1 solidifies in 4 min during a sand-casting operation.

1. What will be the solidification time if the cylinder height is tripled?
2. What will be the solidification time if the cylinder diameter is tripled?
3. In turns out that the optimum shape of a riser is spherical to ensure that it cools more slowly than the related casting. Spherically shaped risers, however, are difficult to cast.
    a. Sketch the shape of a blind riser that is easy to mold, but also has the smallest possible surface area-to-volume ratio.
    Hint. A closed or blind riser is a riser that is contained within the mold. It has no direct contact with the atmosphere.
    b. Compare the solidification time of the riser you designed to that of a riser shaped like a simple cylinder. Assume that the volume of each riser is the same ($V = V_s$, where V is the volume of a cylindrical riser with height equal to its radius and V_s the volume your optimized riser).
    Hint. Consider an arbitrary unity volume, $V = V_s = 1$ and remember that for both the radius-to-cylinder height ratio is equal to 1.

11. Turning a Ti-Alloy Rod

A titanium-alloy rod of length $l = 150$ mm and diameter $\emptyset_i = 75$ mm is being radially reduced to a diameter $\emptyset_f = 65$ mm by turning on a lathe in one pass. The spindle rotates at $v_s = 400$ rpm and the tool is traveling at an axial velocity of $v_a = 200$ mm/min. Consider that the unit energy required has an average value of $E_{av} = 3.5\ \mathrm{W \cdot s/mm^3}$.

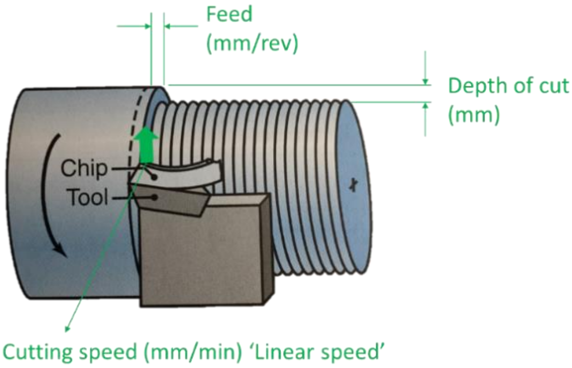


Figure 14. *Representation of the cutting process.*

1. Calculate the material removal rate.
2. How long does it take for this machining operation to be completed?
3. What is the required power?
4. What is the loading mode in the rod? Characterize and calculate the cutting force F_c.

[4] *Adapted from Kalpakjian, Schmid,* Manufacturing Processes for Engineering Materials, *6th Edition, Pearson Ed.*

12. Tool Wear with Ceramics

Using the Taylor equation for tool wear and choosing an average value out of the possible n values for tools in ceramics, calculate the percentage increase in tool life if the cutting speed is reduced by (a) 30% and (b) 60%.

13. Drilling Holes in a Block of Magnesium

(Adapted from the final exam 2018)

A hole is being drilled in a block of magnesium alloy of thickness $t_b = 2 \text{ cm}$, with a $\emptyset_d = 15 \text{ mm}$ drill in high-speed steel ($\sigma_{y,HSS} = 1000 \text{ MPa}, E_{HSS} = 200 \text{ GPa}, \nu_{HSS} = 0.29$) at a feed of $f = 0.20 \text{ mm/rev}$. The spindle is running at $v_s = 500 \text{ rpm}$.
Consider that the unit energy required has an average value of $E_{av} = 0.5 \text{ W} \cdot \text{s/mm}^3$.

1. Express the MRR for a drill bit of diameter $\emptyset_d$, a feed rate f and spindle rotational speed v_s.
2. Calculate the MRR, and estimate the torque on the drill.
3. Express and compute the angle of twist ϕ seen by the drill during the process as a function of the given parameters.

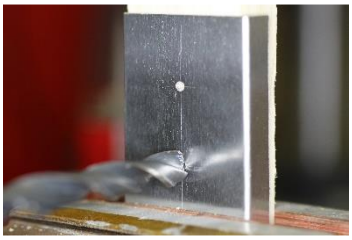


Figure 15. *Drilling process.*

14. Cutting Test on a Steel Bar

(Adapted from the final exam 2024)

A cutting test on a steel bar was performed, and the following values were reported:

- $F_c = 680$ N the shear force
- $F_t = 380$ N the thrust force
- R the resultant force
- F_s the shear force on shear plane
- F the friction force along rake plane
- N the normal force to rake face
- $\phi = 25.0°$ the shear angle
- $\alpha = 10.0°$ the rake angle
- β the mean friction angle

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1. Draw a force diagram at the tool-chip-work interface, to scale, to show the graphical relationship between these parameters.

For this test, the following values were noted:

- $w = 3.50$ mm the width of cut
- $t_0 = 0.210$ mm the undeformed chip thickness
- t_c the deformed chip thickness

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2. Compute (a) the reaction force R, (b) the friction angle β, (c) the shear force on shear plane F_s, (d) the friction force along rake face F, (e) the normal force to rake face N, (f) the apparent shear stress τ_s, (g) the apparent friction coefficient μ and (h) the cutting ratio r.
3. The cutting speed was $V = 1.00$ m/s and the mass flow rate $m = 3.50$ g/s. Specific heat capacity of the work material is $C = 500$ J/kg/°C. Determine the temperature T_s **at the shear plane** assuming 90% of heat is transported with the chip and the original work material temperature was $T_o = 20$°C.
   - The power dissipated through the chip is $P_{chip} = mC\Delta T$.
   - You can use the law of sines applied to the velocity diagram:
   $$\frac{V}{\cos(\phi - \alpha)} = \frac{V_s}{\cos(\alpha)} = \frac{V_c}{\sin(\phi)}$$
   where V is the cutting speed, V_s is the speed at which shearing takes place in the shear plane and V_c is the speed of the chip.
4. Where is the maximum temperature in orthogonal cutting located? Note that there are two principal sources of heat: the shear plane and the tool-chip interfaces.
5. Compute the chip velocity V_c and chip thickness t_c.
6. Answer to the following questions in a few words:
   a. How does the coolant help the cutting process in terms of mechanical properties?
   b. What action may be taken to reduce the rise in coolant temperature in a turning operation, without changing the turning parameters?
7. True or false? Please justify your answers!
   a. For the same depth of cut and rake angle, the type of cutting fluid used has no influence on chip thickness.
   b. High-speed cutting can be performed without the use of cutting fluids.

15. Lead-Frames Manufacturing in Electronics

Lead frames are used to support integrated circuits as illustrated below. They are essential tools for a variety of electronics products as well as MEMS. A lead frame consists of a metal structure on which the silicon die is attached to, and then, electronically interconnected using wire bonding.

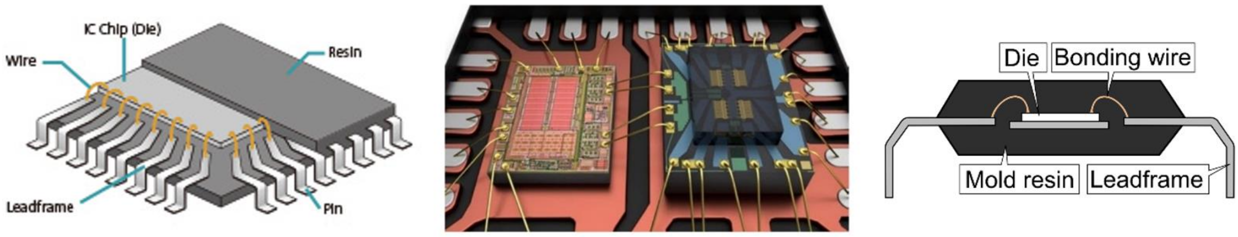


Figure 16. *Left: structure of a lead-frame package (source: Toppan Printing Co.). Centre: picture of wire bonded chips (source: allaboutcircuits.com). Right: wire bonding technique for chips packaging (source: Wiki).*

Here, we discuss the fabrication of the naked lead frame itself (the metal part alone). The purpose of this exercise is to practice process selection and critically identify suitable manufacturing processes for a given product. Examples of such lead frames are shown below.

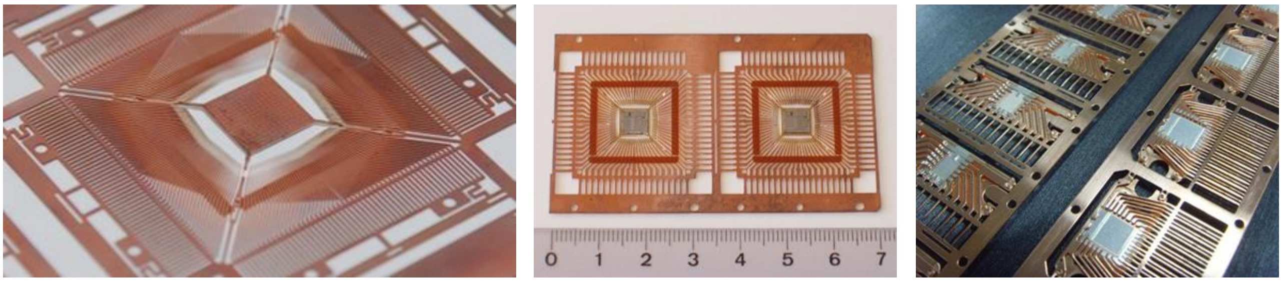


Figure 17. *Left: high-density lead-frame. Centre: lead-frame for chips mounted vertically with respect to the electronic board, typically when a cooling element is needed. Right: classical lead-frame for IC mounted on the surface of the board. Sources: Wiki (left and centre), METS (right).*

1. Discuss the optimal choice of material for lead-frames. Which physical properties are relevant in this context and should be optimized? Is there any better material than lead that one could use? Follow the methodology learned in the first exercise. Use the Granta EduPack software to generate a useful Ashby plot (available on the STI-WINDOWS10 virtual machine).
2. Select four possible processes that would work for producing these parts and discuss for each of them what would be the pros and cons.
3. Among your propositions and arguing with logical arguments, propose one process (or two) that are likely to be chosen for such application. Try to guess which process was used for each of the three examples on the figure.

16. Estimation of the Production Cost for a LEGO™ Brick

(Inspired from John Hart, MIT)

The purpose of this exercise is to estimate the cost for producing LEGO bricks.

The following information are provided:

- *Material:* ABS
- *Density:* $\rho_{ABS} = 1000 \text{ kg} \cdot \text{m}^{-3}$
- *Raw ABS cost:* $3.50 \text{ \$} \cdot \text{kg}^{-1}$
- *Basic overhead:* $10 \text{ \$} \cdot \text{h}^{-1}$
- *Injection molding cycle time:* $\sim 6 \text{ s}$
- *Mold cost (for 8 bricks):* $\sim 35\,000 \text{ \$}$
- *Machine cost:* $\sim 200\,000 \text{ \$}$ *(with a depreciation time of* 10 *years)*
- *Void volume fraction of a single brick:* 65.6%

Typical dimensions for a LEGO brick are shown in the side figure.

This YouTube video illustrates how LEGO bricks are made: https://youtu.be/y1Zhpdx-XtA.

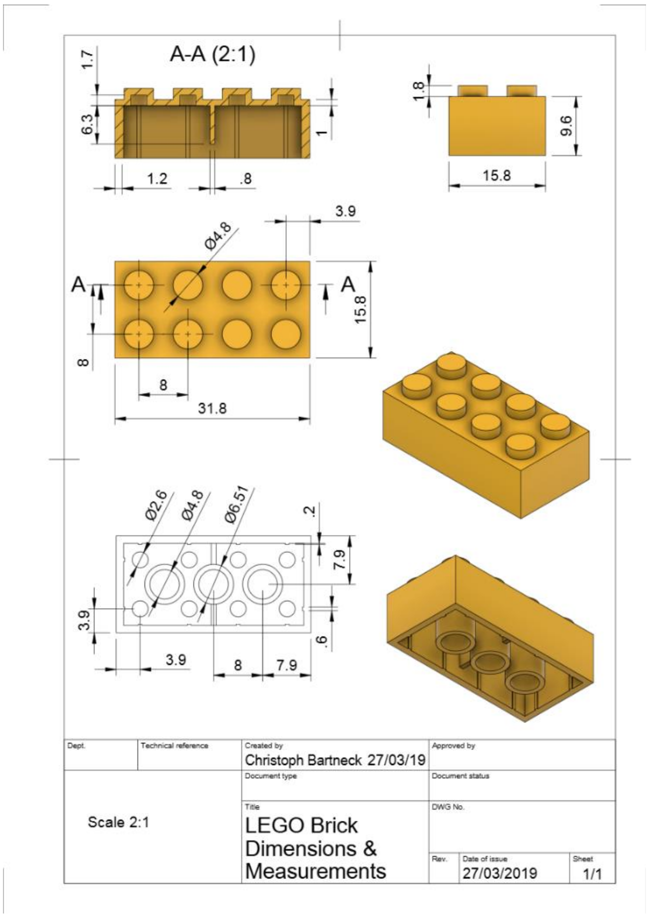


Figure 18. *Typical dimensions of a LEGO brick that can be used to estimate relevant volumetric parameters.*

1. Write the equation for the total shaping cost per part with its four terms (real cost of manufactured material C_{mm}, cost of tooling (or dedicated cost) $C_{tooling}$, capital rate $\dot{C}_{capital}$ and overhead rate $\dot{C}_{oh}$), as a function of the number of parts produced n and production rate $\dot{n}$.
2. Develop this general equation with the literal relations seen in the lecture on manufacturing economics. Make sure to identify which expression corresponds to which term.
3. Calculate the cost of a brick considering a production level of (a) 1000 parts, (b) 100 000 parts, and (c) 10 000 000 parts.

17. Estimation of the Production Cost for Laser Processed Parts

We consider the laser processing of glass made by combining femtosecond lasers and chemical etching. Details about this process are discussed in the lecture on laser manufacturing and in a previous exercise. Our goal is to estimate the cost for producing a part using this advanced manufacturing technology and discuss a way of lowering production costs.

Our working hypothesis are:

- *Material:* fused silica glass
- *Raw material cost:* $\sim 10\ \mathrm{CHF} \cdot \mathrm{substrate}^{-1}$
- *Basic overhead:* $\sim 10\ \mathrm{CHF} \cdot \mathrm{h}^{-1}$
- *Machine cost:* $\sim 400\,000\ \mathrm{CHF}$ *(with a depreciation time of* 5 *years)*
- *Processing time:* $\sim 1\ \mathrm{h} \cdot \mathrm{part}^{-1}$
- *We assume that* 4 *parts per substrate can be produced*

1. What should be the selling price per part for a batch of 1000 parts with a 30% profit margin?
2. How could we reduce the production cost?

18. Brush-Up on Statistics

Let us consider a drill bit and do the following assumptions:

- The drill bit's lifetime can be modelled by a normal distribution
- It has an average lifetime of 5000 holes
- It has a standard deviation of 500 holes

Figure 19. *A drill bit.*

1. What fraction of drill bits are likely to wear out after (a) 4500 holes? (b) 5500 holes? (c) 6000 holes? Please use the z-scores table provided on the next page.
2. What fraction of drill bits will wear out at exactly the 5725th hole?
3. Suppose that 68% of the drill bits have a diameter comprised between 3.88 and 4.24 mm. Averages of five successive drill bits were measured, and 40% of these were observed to lie between 4.06 and A mm. Estimate the value of A (state the assumptions you make and say whether these assumptions are likely to be true for this example).
   Note. You may want to use online calculators for normal distributions to *compute the area under the curve* *or* *any parameter of a normal distribution*.

z-scores table

z	+0.00	+0.01	+0.02	+0.03	+0.04	+0.05	+0.06	+0.07	+0.08	+0.09
0.0	0.00000	0.00399	0.00798	0.01197	0.01595	0.01994	0.02392	0.02790	0.03188	0.03586
0.1	0.03983	0.04380	0.04776	0.05172	0.05567	0.05962	0.06356	0.06749	0.07142	0.07535
0.2	0.07926	0.08317	0.08706	0.09095	0.09483	0.09871	0.10257	0.10642	0.11026	0.11409
0.3	0.11791	0.12172	0.12552	0.12930	0.13307	0.13683	0.14058	0.14431	0.14803	0.15173
0.4	0.15542	0.15910	0.16276	0.16640	0.17003	0.17364	0.17724	0.18082	0.18439	0.18793
0.5	0.19146	0.19497	0.19847	0.20194	0.20540	0.20884	0.21226	0.21566	0.21904	0.22240
0.6	0.22575	0.22907	0.23237	0.23565	0.23891	0.24215	0.24537	0.24857	0.25175	0.25490
0.7	0.25804	0.26115	0.26424	0.26730	0.27035	0.27337	0.27637	0.27935	0.28230	0.28524
0.8	0.28814	0.29103	0.29389	0.29673	0.29955	0.30234	0.30511	0.30785	0.31057	0.31327
0.9	0.31594	0.31859	0.32121	0.32381	0.32639	0.32894	0.33147	0.33398	0.33646	0.33891
1.0	0.34134	0.34375	0.34614	0.34849	0.35083	0.35314	0.35543	0.35769	0.35993	0.36214
1.1	0.36433	0.36650	0.36864	0.37076	0.37286	0.37493	0.37698	0.37900	0.38100	0.38298
1.2	0.38493	0.38686	0.38877	0.39065	0.39251	0.39435	0.39617	0.39796	0.39973	0.40147
1.3	0.40320	0.40490	0.40658	0.40824	0.40988	0.41149	0.41308	0.41466	0.41621	0.41774
1.4	0.41924	0.42073	0.42220	0.42364	0.42507	0.42647	0.42785	0.42922	0.43056	0.43189
1.5	0.43319	0.43448	0.43574	0.43699	0.43822	0.43943	0.44062	0.44179	0.44295	0.44408
1.6	0.44520	0.44630	0.44738	0.44845	0.44950	0.45053	0.45154	0.45254	0.45352	0.45449
1.7	0.45543	0.45637	0.45728	0.45818	0.45907	0.45994	0.46080	0.46164	0.46246	0.46327
1.8	0.46407	0.46485	0.46562	0.46638	0.46712	0.46784	0.46856	0.46926	0.46995	0.47062
1.9	0.47128	0.47193	0.47257	0.47320	0.47381	0.47441	0.47500	0.47558	0.47615	0.47670
2.0	0.47725	0.47778	0.47831	0.47882	0.47932	0.47982	0.48030	0.48077	0.48124	0.48169
2.1	0.48214	0.48257	0.48300	0.48341	0.48382	0.48422	0.48461	0.48500	0.48537	0.48574
2.2	0.48610	0.48645	0.48679	0.48713	0.48745	0.48778	0.48809	0.48840	0.48870	0.48899
2.3	0.48928	0.48956	0.48983	0.49010	0.49036	0.49061	0.49086	0.49111	0.49134	0.49158
2.4	0.49180	0.49202	0.49224	0.49245	0.49266	0.49286	0.49305	0.49324	0.49343	0.49361
2.5	0.49379	0.49396	0.49413	0.49430	0.49446	0.49461	0.49477	0.49492	0.49506	0.49520
2.6	0.49534	0.49547	0.49560	0.49573	0.49585	0.49598	0.49609	0.49621	0.49632	0.49643
2.7	0.49653	0.49664	0.49674	0.49683	0.49693	0.49702	0.49711	0.49720	0.49728	0.49736
2.8	0.49744	0.49752	0.49760	0.49767	0.49774	0.49781	0.49788	0.49795	0.49801	0.49807
2.9	0.49813	0.49819	0.49825	0.49831	0.49836	0.49841	0.49846	0.49851	0.49856	0.49861
3.0	0.49865	0.49869	0.49874	0.49878	0.49882	0.49886	0.49889	0.49893	0.49896	0.49900
3.1	0.49903	0.49906	0.49910	0.49913	0.49916	0.49918	0.49921	0.49924	0.49926	0.49929
3.2	0.49931	0.49934	0.49936	0.49938	0.49940	0.49942	0.49944	0.49946	0.49948	0.49950
3.3	0.49952	0.49953	0.49955	0.49957	0.49958	0.49960	0.49961	0.49962	0.49964	0.49965
3.4	0.49966	0.49968	0.49969	0.49970	0.49971	0.49972	0.49973	0.49974	0.49975	0.49976
3.5	0.49977	0.49978	0.49978	0.49979	0.49980	0.49981	0.49981	0.49982	0.49983	0.49983
3.6	0.49984	0.49985	0.49985	0.49986	0.49986	0.49987	0.49987	0.49988	0.49988	0.49989
3.7	0.49989	0.49990	0.49990	0.49990	0.49991	0.49991	0.49992	0.49992	0.49992	0.49992
3.8	0.49993	0.49993	0.49993	0.49994	0.49994	0.49994	0.49994	0.49995	0.49995	0.49995
3.9	0.49995	0.49995	0.49996	0.49996	0.49996	0.49996	0.49996	0.49996	0.49997	0.49997
4.0	0.49997	0.49997	0.49997	0.49997	0.49997	0.49997	0.49998	0.49998	0.49998	0.49998

19. Process Control Values[5]

We consider the set of data given in **Figure 20** that shows length measurements (in mm) taken on a machined workpiece. The sample size is 5 and the number of samples is 10, thus the total number of parts measured is 50. The quantity $\bar{x}$ is the average of five measurements in each sample.

Sample number	x_1	x_2	x_3	x_4	x_5	$\bar{x}$	R
1	113.3	111.8	112.8	113.3	112.5	112.74	1.5
2	113.0	112.5	113.5	111.5	111.8	112.46	2.0
3	111.3	113.8	112.3	112.3	110.5	112.09	3.3
4	112.3	112.8	115.2	114.0	110.5	112.94	4.6
5	112.3	113.0	112.5	112.8	112.0	112.52	1.0
6	112.8	113.0	112.8	111.5	111.8	112.38	1.5
7	111.5	112.0	112.3	113.3	113.5	112.52	2.0
8	113.0	112.0	112.5	112.0	114.3	112.76	2.3
9	112.8	113.3	109.2	111.3	114.0	112.12	4.8
10	112.3	112.5	111.0	113.5	114.0	112.60	3.0

Figure 20. *Data set on the length of machined workpieces.*

1. Determine the upper and lower control limits and standard deviation for this population.
2. What are the consequences of setting the lower and upper specifications closer to the average values $\bar{\bar{x}}$ and $\bar{R}$?
3. Identify at least five factors that can cause a process to become out of control. You can discuss several processes.

20. Cost of Quality

High-quality polymer tubes are being produced for medical applications in which the target wall thickness is $2.6\ \mathrm{mm}$, a UCL was set to $3.2\ \mathrm{mm}$, and an LCL to $2.2\ \mathrm{mm}$. If the units are defective, they are replaced at a shipping-included cost of 10 €. The current process produces parts with a mean value of $2.6\ \mathrm{mm}$ and a standard deviation of $0.2\ \mathrm{mm}$. The current volume is $10'000$ sections of tube per month. An improvement is being considered for the extruder heating system: it would cut the variation in half, but costs $50'000$ € to implement.

1. Is it correct to assume that the target wall thickness with its tolerances is $t = 2.6^{+0.6}_{-0.4}\ \mathrm{mm}$?
2. Determine the Taguchi loss function and the payback period for the investment.
3. Discuss the advantages and disadvantages of the Taguchi method.

[5] *Adapted from Kalpakjian, Schmid,* Manufacturing Processes for Engineering Materials*, 6th Edition, Pearson Ed.*

21. Assembly Cost Analysis: The Staple Remover[6]

The figure below shows an exploded view of a stapler remover, with its various components. The purpose of this exercise is to analyze the assembly cost of this object. You will have to do the same type of analysis as part of your reverse engineering project.

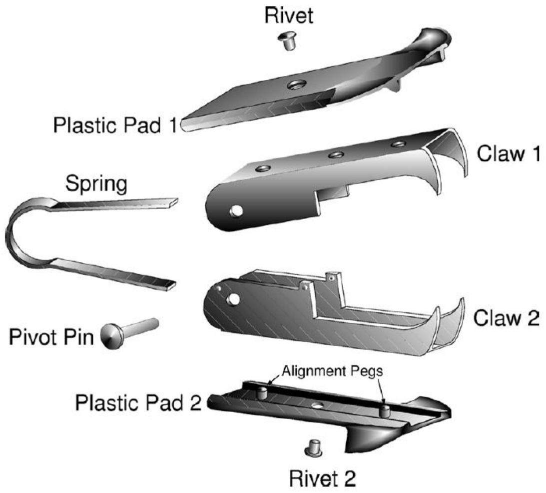


Figure 21. *Exploded view of a staple remover.*

1. Generally speaking, how would you define what is a sub-assembly?
2. As a first step, define sub-assemblies and make a graph of the assembly.
3. Using your graph, analyze the manual assembly operations and make a cost estimate of it. Assume a labour cost of $C_L = 0.02\ \mathrm{CHF} \cdot \mathrm{s}^{-1}$. Use the Excel table available on Moodle!

[6] *Adapted from Swift, Booker,* Manufacturing Process Selection Handbook*, 1st Edition, Butterworth-Heinemann*

22. Assembly & Mobility Analysis of an Optical Mount

We consider an optical mount as shown in **Figure 22** below. These types of mounts are broadly used in optical engineering to change the orientation of optical component like mirrors for instance. In this exercise, we propose to analyze the kinematics of such system. The nature of the contact between the two main parts is also indicated in the figure.

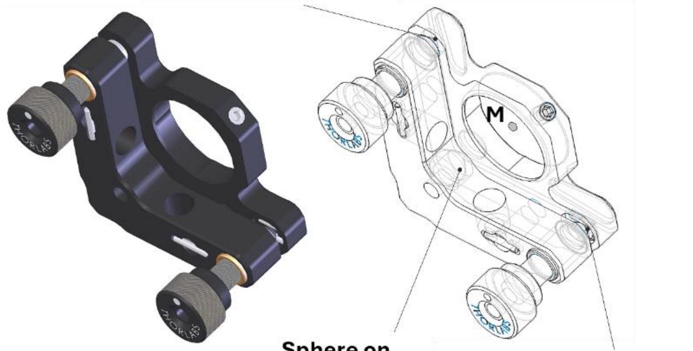


Figure 22. *An optical mount for optical components positioning (CAD models are from Thorlabs website).*

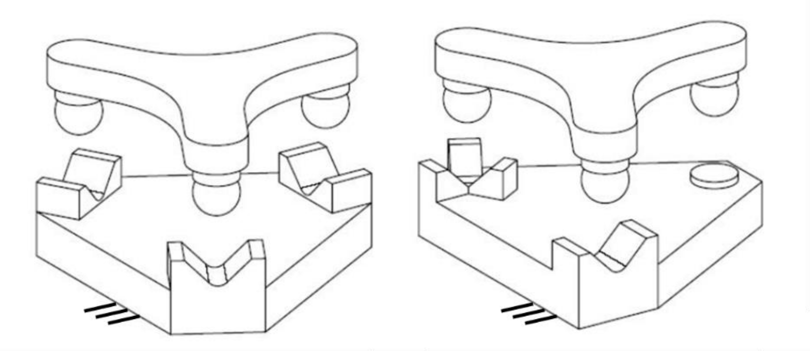
Download the Auto CAD PDF document available on the website (Thorlabs - KM100CP/M Kinematic Mirror Mount for Ø1" Optics with Post-Centered Front Plate, M4 Taps). To visualize the part in 3D, you can download the Solidworks file of the part, but it is quicker to click on the eDrawing link (also provided on the website).

1. Explain how the two main parts are held together.
2. Draw the graph of this mechanism and do the mobility analysis (a) considering the ball as an independent body, (b) considering the ball as part of the base body.
3. Locate the position of the center of rotation.
4. Assume that the distance between the sphere on the lower left corner and the two other spheres is the same and is called L. Additionally, assume that the point M is in the middle of the optical mount at a distance $L/2$ away of the two orthogonal axes formed by the three spheres.
   a. What is the trajectory of point M?
   b. Is the mirror doing perfect rotations? If not, express the amplitudes of the parasitic motions ε_x and ε_y as a function of a small motion of the adjusters δ and L.
   c. How could we get rid of any parasitic motions?

23. The Kinematics Couplers

(Adapted from the final exam 2019)

The purpose of this exercise is to analyze from a mobility point-of-view a theoretical kinematics coupler and then to discuss its practical realization from a manufacturing point of view.



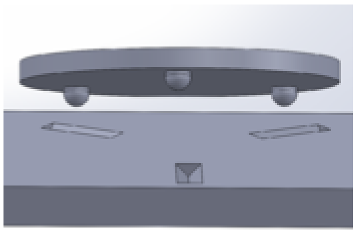
Maxwell kinematics coupling **Kelvin kinematics coupling**

Figure 23. *Schematic representation of a Maxwell (left) and a Kelvin (right) kinematics couplings. Note that manufactured one may look different, but the working principles are the same: three contact points with particular geometries.*

23.1. Couplers Analysis

1. Using graph theory and mobility analysis with CGK formula, show that both systems are kinematically equivalent. We expect a graph for each system, and calculation of their mobility.
2. Discuss the general function of these devices and their specific purposes.
3. Assume that instead of the triangular shape for the detachable element (as shown in **Figure 23**), a simple cylindrical plate is now used and contains the spherical contacts (as shown below). In such case, can a vertical load (i.e. oriented perpendicular to the plane of the mechanism) be applied at any point on the disk? Comment on it.

Figure 24. *Schematic of a Maxwell coupling realized with a detachable cylindrical element.*



4. Discuss the important physical parameters (i.e. intrinsic properties of the materials) to optimize when selecting the materials for:
    a. The detachable plate to minimize deflection and maximize structural stability
    b. The surfaces in direct contact
    c. Maximizing the accuracy of the system while in operation under varying temperature
    d. Heavy load operation while being lightweight
5. What advantage / disadvantage do you see for each mechanism when comparing them?

23.2. Reverse Engineering

The picture and CAD rendering below illustrate an example of kinematics coupling commercial product for optical applications. In this section, we discuss the technical choices that were made.

Figure 25. *Illustration of a product from Thorlabs. Left: detached configuration showing the inside of the device. The flat and circular parts in the middle are magnets. Right: coupled configuration.*

6. To what type of coupling is this device equivalent to?
7. What manufacturing operations have been used for the main parts (in black)? Discuss a credible fabrication process sequence as well as a possible assembly sequence, and the choices that were made (in particular regarding the pins orientation).

24. Soldering Processes

The purpose of this exercise is to investigate the impact of the physical and material properties of chips, packages and solders. In particular, we emphasize the use of simplifying assumptions to allow you to quickly draw conclusions. You are encouraged to consider more complex formulations on your own to see how much these assumptions impact accuracy.

Consider the use of a eutectic Pb-Sn solder and the phase diagram below.

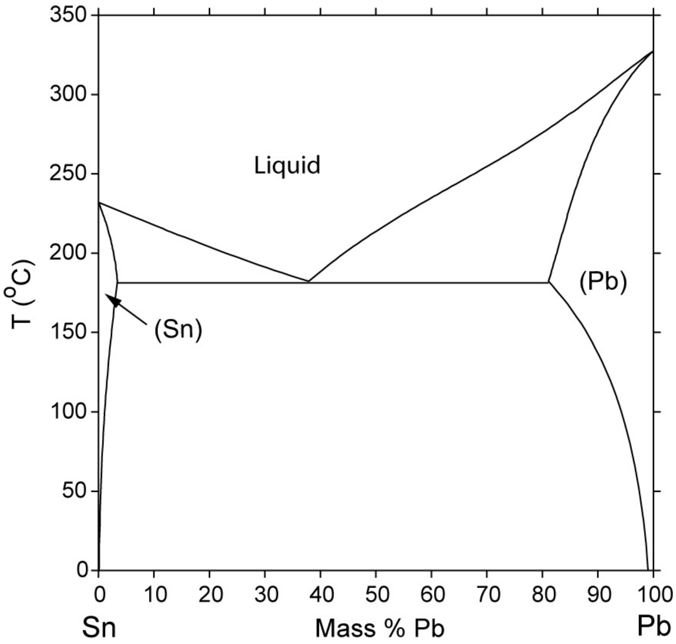


Figure 26. *Pb-Sn phase diagram.*

1. What is the melting temperature of this solder?
2. Suppose we are using this solder to form a connection between a pad on a PCB and a pad on an integrated circuit. Assume that we are using this connection in an audio amplifier that is intended to drive an $8\ \Omega$ loudspeaker at $100\ \mathrm{W}$. What is the current flowing through the solder?
3. Assume both pads are $50\ \mu\mathrm{m}$ squares, and that the thickness of the connection is also $50\ \mu\mathrm{m}$ (in other words, assume the solder forms a cube that is $50\ \mu\mathrm{m}$ on each side). Ignoring any heat losses through the pads, what is the maximum amount of time that this current can flow through the pads without the solder re-melting during operation?
   Hint. You may find the following information useful:
   - *Electrical resistivity of Sn-37Pb:* $0.153\ \mu\Omega \cdot \mathrm{m}$
   - *Specific heat capacity of Sn-37Pb:* $0.21\ \mathrm{J} \cdot \mathrm{g}^{-1} \cdot {}^{\circ}\mathrm{C}^{-1}$
   - *Density of Sn-37Pb:* $8.4\ \mathrm{g} \cdot \mathrm{cm}^{-3}$
   - *Assume we start at* $25^{\circ}\mathrm{C}$
   - *Ignore the difference between liquidus and solidus, i.e., just use the lower bound*
4. Clearly, this is an oversimplification, and in fact, the time to melt is much longer in reality. Why?
5. If we wanted to include the effect of heat loss, what equations would we include in our model to determine the relationship between current flowing through the connection and the onset of melting? Assume steady state conditions.

6. Even when we use more accurate analysis, it turns out that Sn-37Pb is not good for such high current applications, and we are therefore forced to use solders capable of handling higher temperature. Suppose we were to use a solder with a higher percentage of Pb (e.g., 60% Pb solder). At $185°C$ (i.e., just above the eutectic line), what phase(s) is (are) present and at what compositions?
7. What is the relative amount of each phase present, in mass fraction?
8. What components would you find in the solid upon solidification of the solder to just below the eutectic line, at with what mass fractions?
9. Would you expect this solder to have better thermal performance under high current conditions? Give reasons.

Consider the use of solder balls to form connections for a modern integrated circuit chip to a package. Assume the pads are $20\ \mu m$ squares, with $10\ \mu m$ spacing between the pads. For simplicity, assume that the solder balls are perfect spheres with diameter of $20\ \mu m$ when the chip is placed in contact with the package. Therefore, at this initial point of contact, the separation between the plane of the chip pad and the package pad is exactly $20\ \mu m$. For all the questions below, use 2D analysis (i.e. there is no need to do 3D calculations). You may find the figure in Slide 50 of the packaging course notes useful.

10. Pressure is applied to the chip to form a good bond, which results in the solder balls being squeezed into ellipses. Assuming area is conserved, what is the die-to-package spacing at which adjacent pads are short circuited?
11. Obviously, we don't want this to happen. Assume the minimum allowable spacing between the ellipses in $5\ \mu m$. What is the die-to-package spacing under this condition?
12. Assume the package is perfectly flat, but the chip has some curvature such that the outermost pads are higher than the center pad. What is the maximum height difference before we obtain open circuits at the edges?