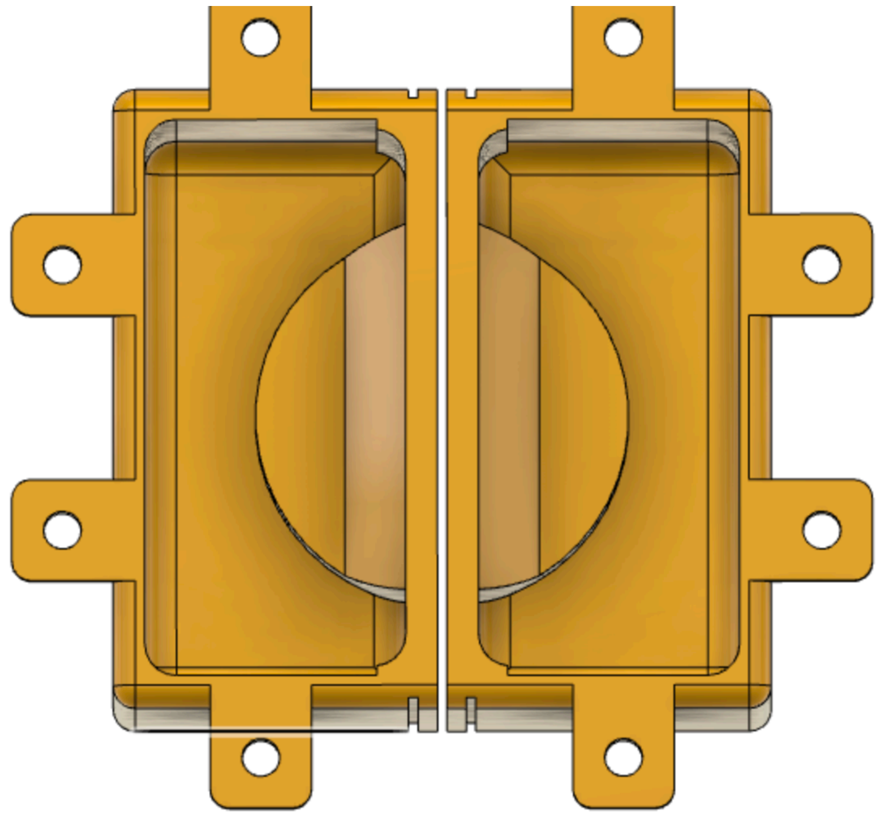
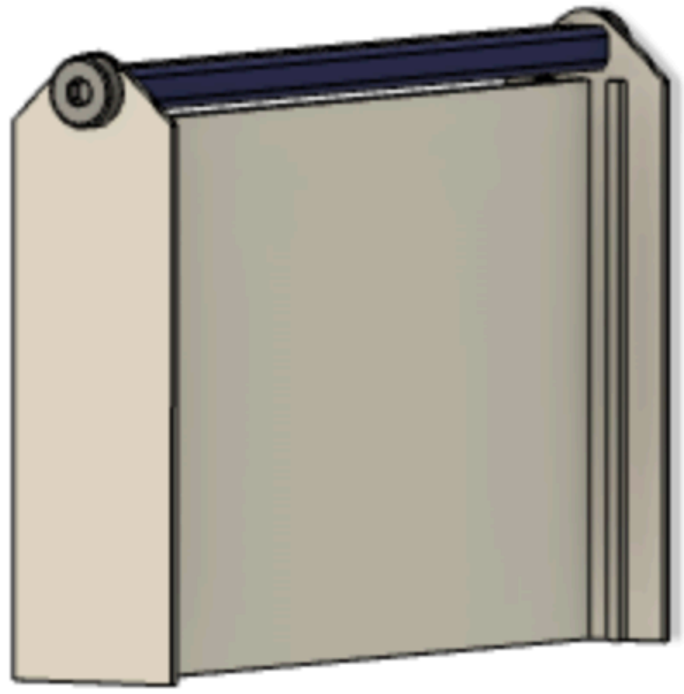
Quarter Bending Mechanism

Design Challenge

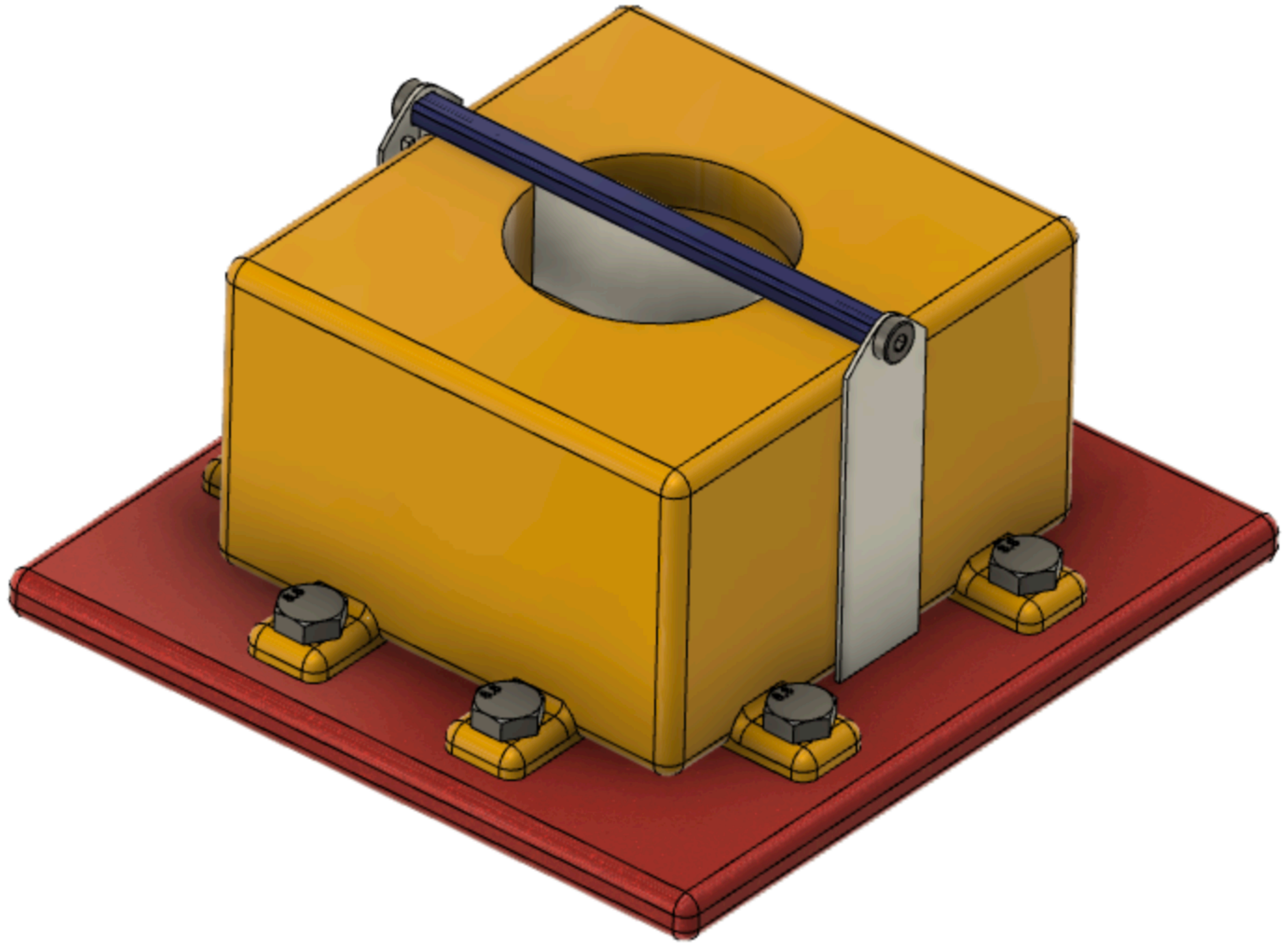
Quarter Pounder



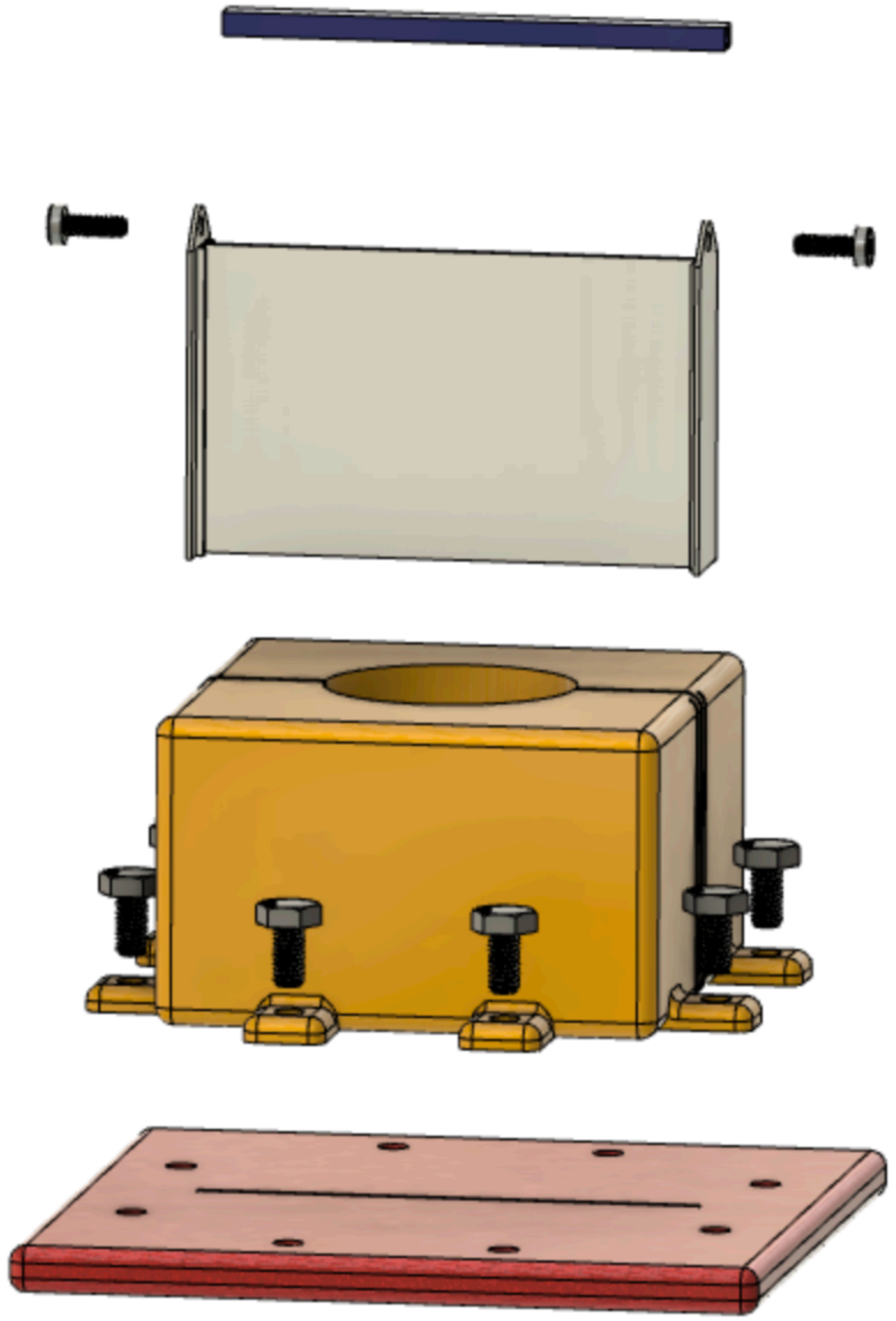
Bottom View



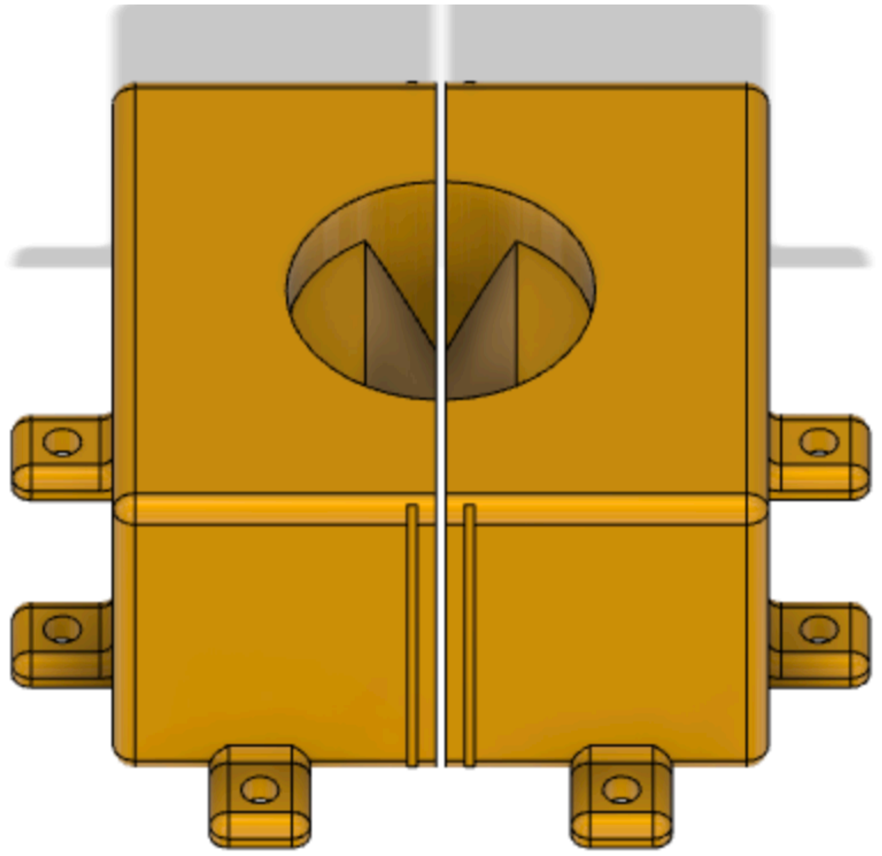
Blade



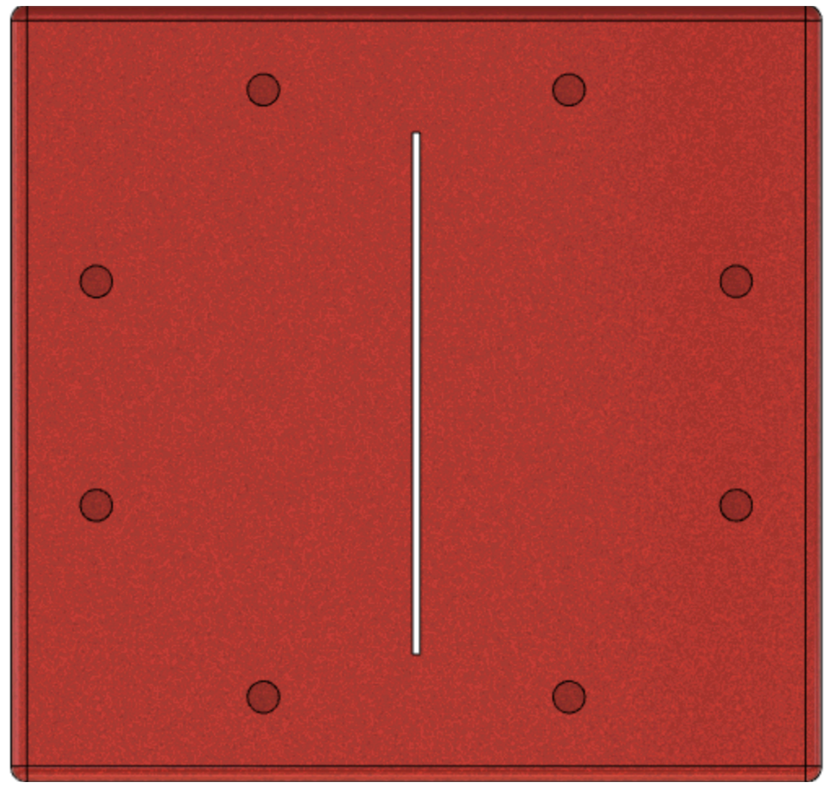
Final Design



Exploded View



Inside Channel View



Plate

Holder: 46 mm x 26.5 mm x 49 mm
Blade: 0.75 mm x 49 mm x 30 mm
Quarter Indent Diameter: 24.3 mm

Quarter Pounder Mechanism

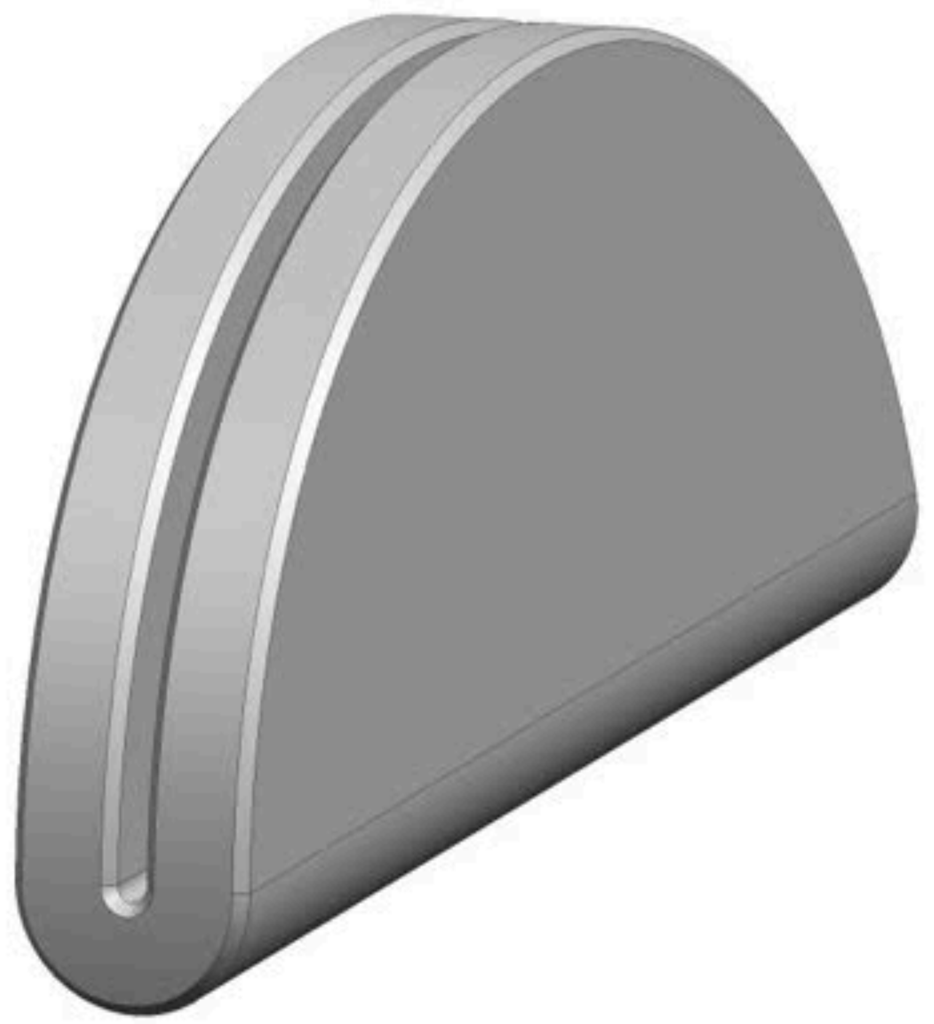
Design Concerns

Risks	Solutions
Open face on the surface of the quarter might cause safety concern when operating blade	Design shield around the blade (aluminum or steel) to prevent quarter from flying out
Channel is too small to be manufacturable	Instead of making two separate parts, make a wider and shorter channel, then incorporate vice jaw into design to complete the full bend
Cracks will appear along the seams of the fold	Stress relieving by heating metal up until below annealing range (700 ˚C - 800 ˚C for CuNi) will reduce likelihood of cracking fatigue
Quarter might be defaced or damaged by sliding down channel	Line channel with silicon to prevent defacing of quarter’s faces

Appendix

Goal

Design a machine that can fold a Quarter (25-cent coin) in half



Needs

- Bends quarter to a bend radius no larger than 0.25 mm
- Two halves on either side of the fold need to be planar to within 5°

Quarter Specs

	Quarter
Composition	8.33% NI Balance Cu
Weight	5.67 g
Diameter	0.955 in 24.26 mm
Thickness	1.75 mm
Edge	Reeded
No. of Reeds	119

Quarter Minting Process

- Ni-plated Cu
- Rolls feed into a blanking machine
- Blanks: plain round discs
- Upsetting mill - raises the rims of the blanks around the edges
- Rim is needed for quarters to stack and to helps blanks hold shape
- Coin press: hammer pounds each blank between two dies

Nickel-Plated Copper

Benefits

- Corrosion Resistance
- Strength
- Increased electrical conductivity (Ni is a good conductor)
- Increased metal’s operating temperature

Cupronickel Properties

Properties of some Cu–Ni alloys[20]

Alloy	Density g/cm^3	Thermal conductivity W/(m·K)	TEC µm/(m·K)	Electrical resistivity µOhm·mm	Elastic modulus GPa	Yield strength MPa	Tensile strength MPa
90–10	8.9	40	17	19	135	105	275
70–30	8.95	29	16	34	152	125	360
66–30–2–2	8.86	25	15.5	50	156	170	435

The alloys are:

UNS standard compositions* of wrought alloys (in at%). Maximum or range.

Alloy UNS No.	Common name	European spec	Ni	Fe	Mn	Cu
C70600	90–10	$CuNi_{10}Fe$	9–11	1–1.8	1	Balance
C71500	70–30	$CuNi_{30}Fe$	29–33	0.4–1.0	1	Balance
C71640	66–30–2–2		29–32	1.7–2.3	1.5–2.5	Balance

Source: *Cupronickel,* Wikipedia

90-10 Copper-Nickel-Iron Alloy

Table 3 90-10 copper-nickel-iron alloy. Mechanical properties. Typical values and ranges. Exact values vary with compositon, size and heat treatment.

Form	Condition	0.1 per cent proof stress		Tensile strength		Elongation on $5.65 \sqrt{S_o}$ per cent	Hardness	Shear strength*	
		N/mm^2	$tonf/in^2$	N/mm^2	$tonf/in^2$		HV10	N/mm^2	$tonf/in^2$
Tube	Annealed	140	9	320	21	40	85	250	16
	Cold drawn (hard)	460	30	540	35	13	165	360	23
	Temper annealed	190-320	12-21	360-430	23-28	38-30	115-140	280-320	18-21
Plate	Annealed	120	8	320	21	42	85	250	16
	Hot rolled	140-190	9-12	340-360	22-23	40	95-105	260	17
Sheet	Annealed	120	8	320	21	42	85	250	16
	Hot rolled	180	12	360	23	40	105	260	17
	Cold rolled	380	25	420	27	12	125	290	19

*Double shear test

https://www.nickelinstitute.org/media/1650/copper_nickelalloys_propertiesandapplications_12007_.pdf

DIY Quarter Measurement Experiment

Question

How do quarters actually vary in size?

What are the tolerances of the quarter?

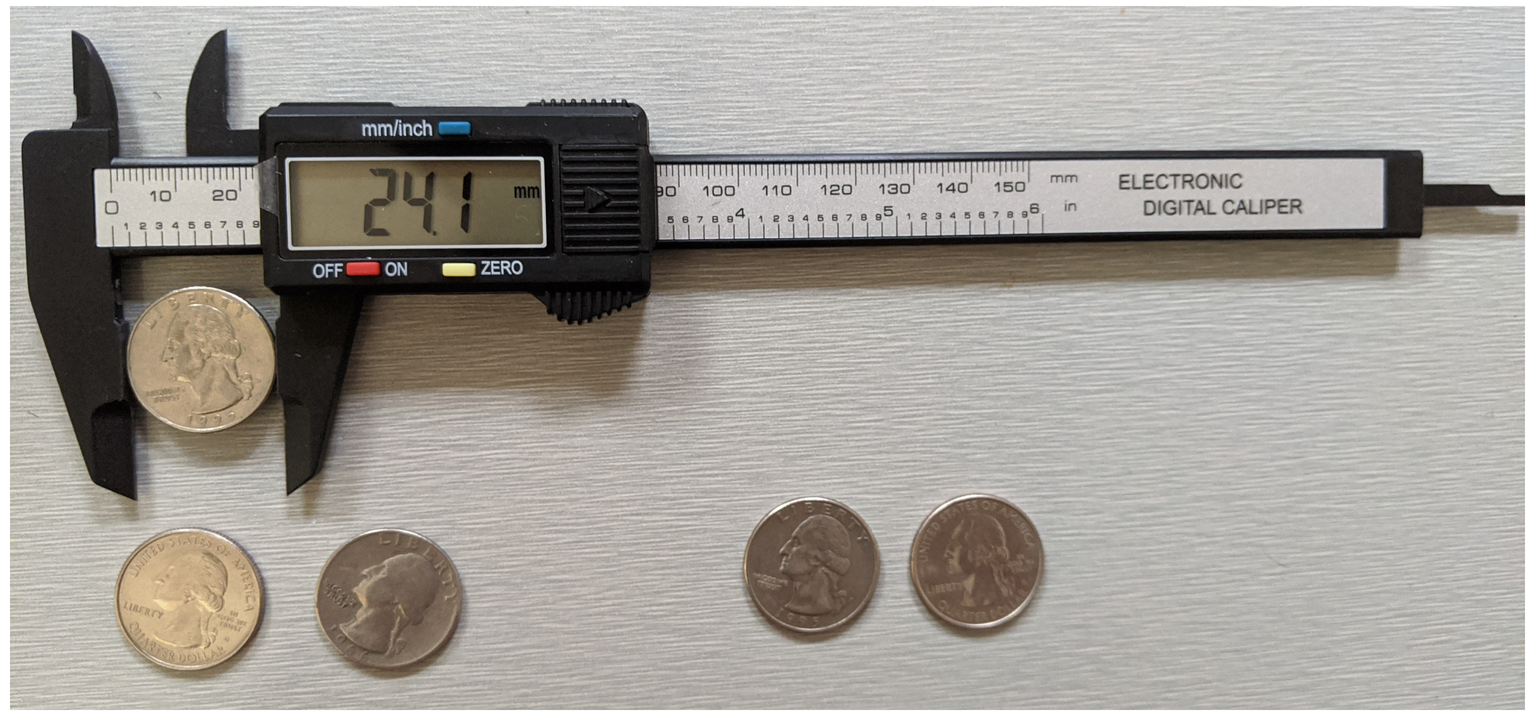
What should the dimensions of the quarter holder be to account for manufacturing differences?

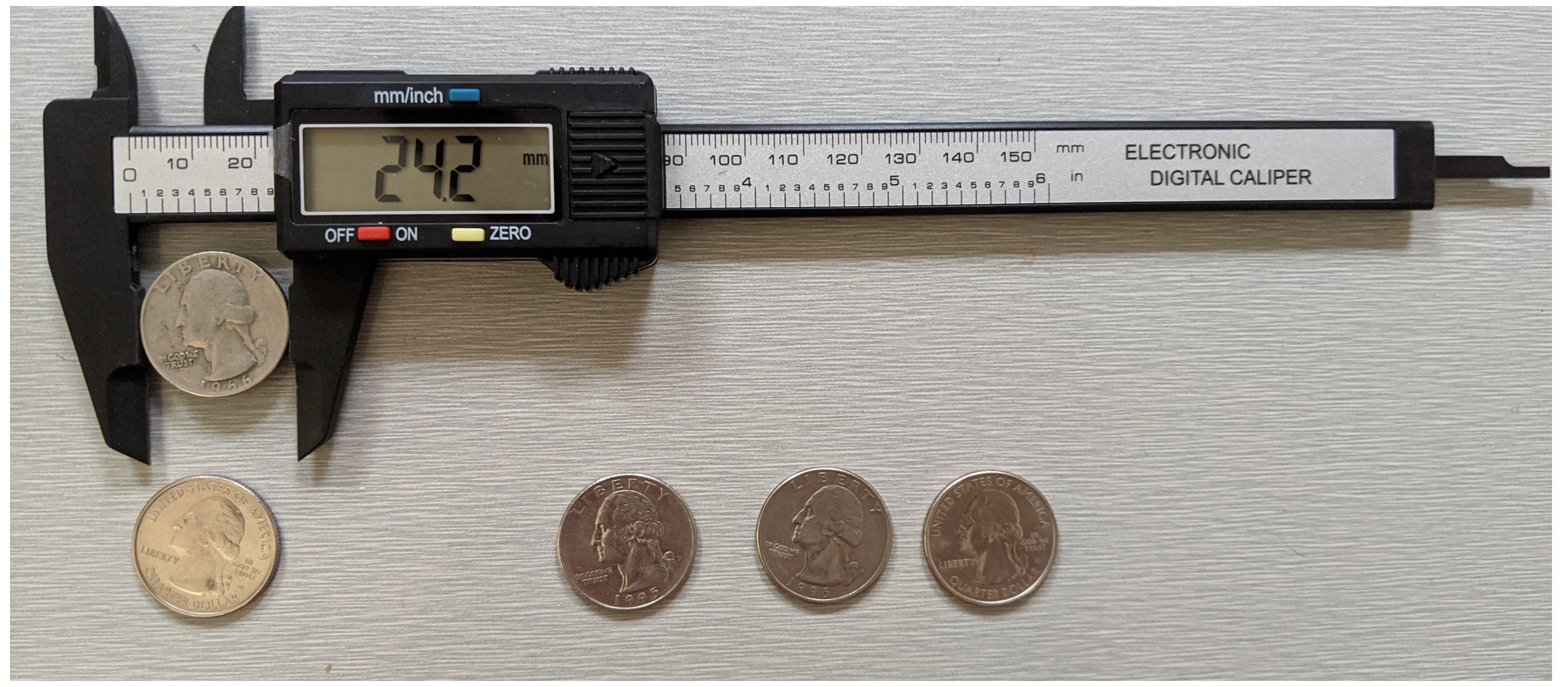
Materials

- Calipers
- Quarters

Conclusions

- Tolerances are ± 0.1 mm
- Design dimension: 24.3 mm to accommodate quarter size





How much force to bend a quarter?

YouTube video:

- 200 lb / 100 kg

https://youtu.be/KrEnWIZ67iQ?t=35

DIY Quarter Bending Experiment

Questions

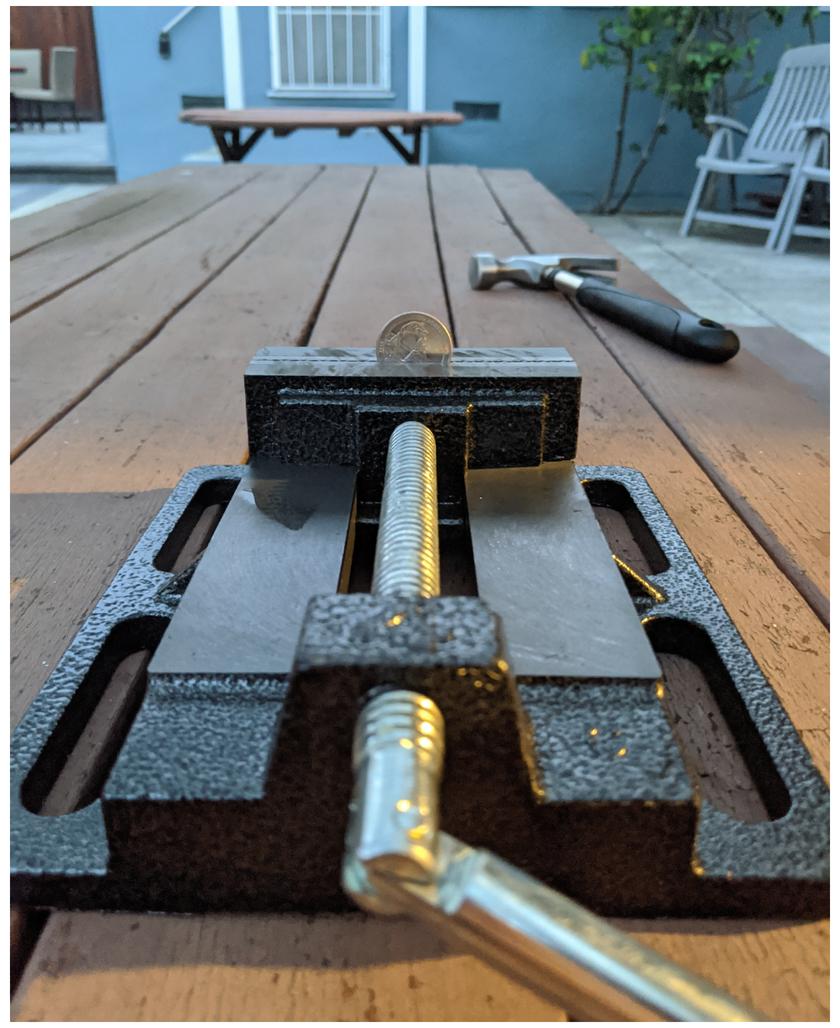
- What do you actually need to do to make a quarter bend?
- What happens to the quarter during the bending process?

Materials

- Vise
- Quarters
- Hammer

Conclusions

- Cracks form along the seam as it bends
- Significantly harder to bend coin from 90° - 180° than from 0° - 90°
- Hard to center the coin by eye and achieve a passable bend at the halfway point
- Need another point of contact to bend the quarter from 90° - 180° to prevent it from popping as it's being bent

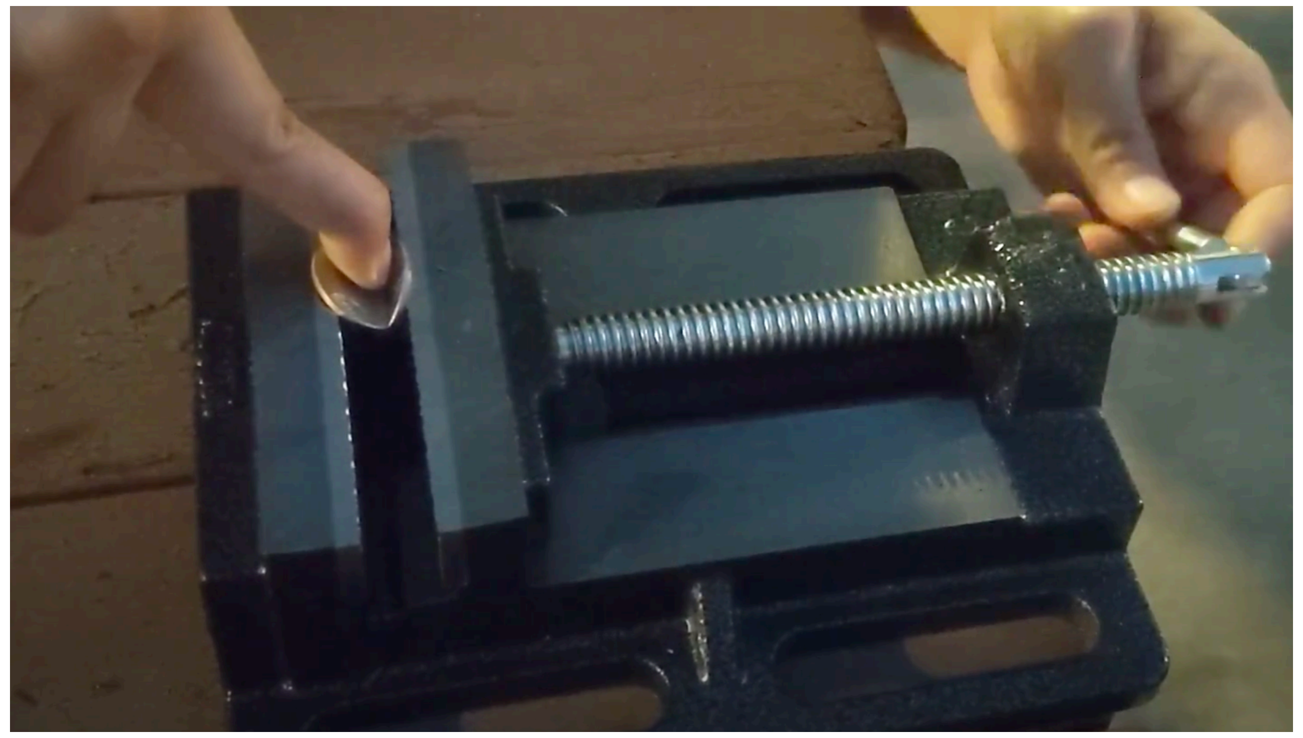


Setup

180° bend (Front View)

Hammer (0° - 90°)

90° Bend

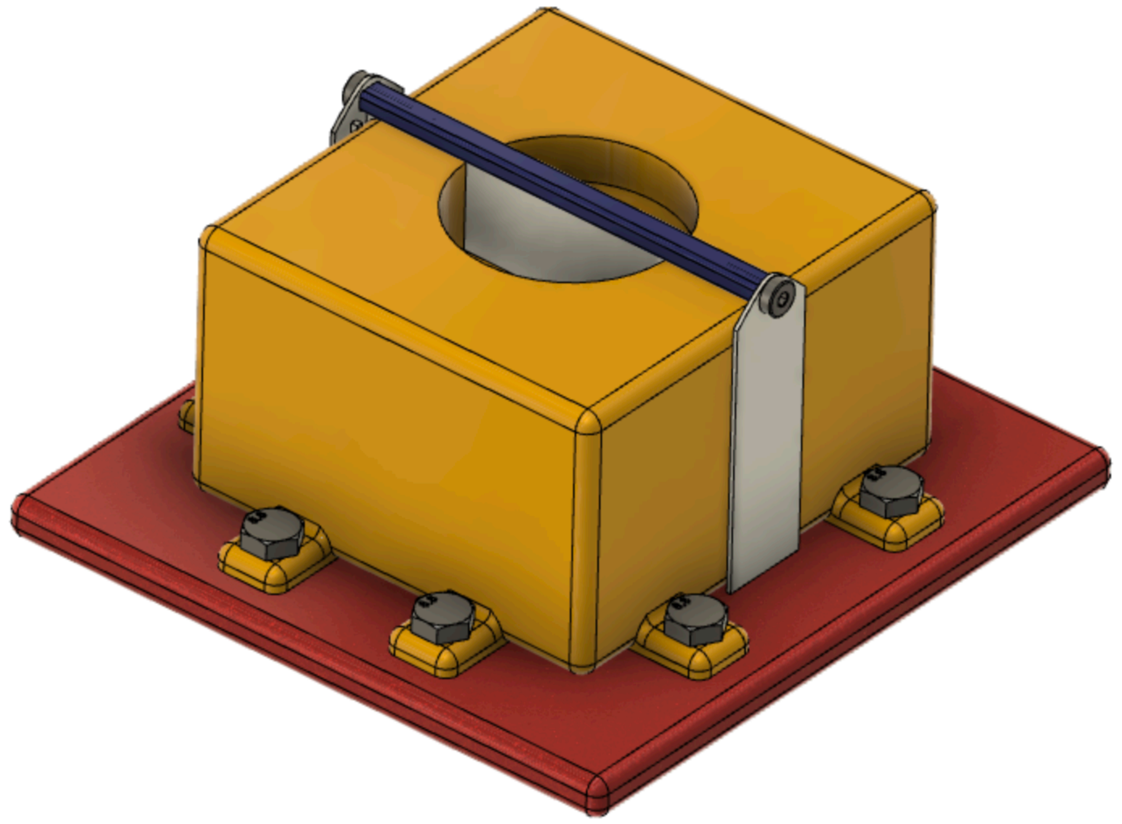


Vise (90° - 180°)

~ 180° Bend (Side View)

Potential Designs

Design A

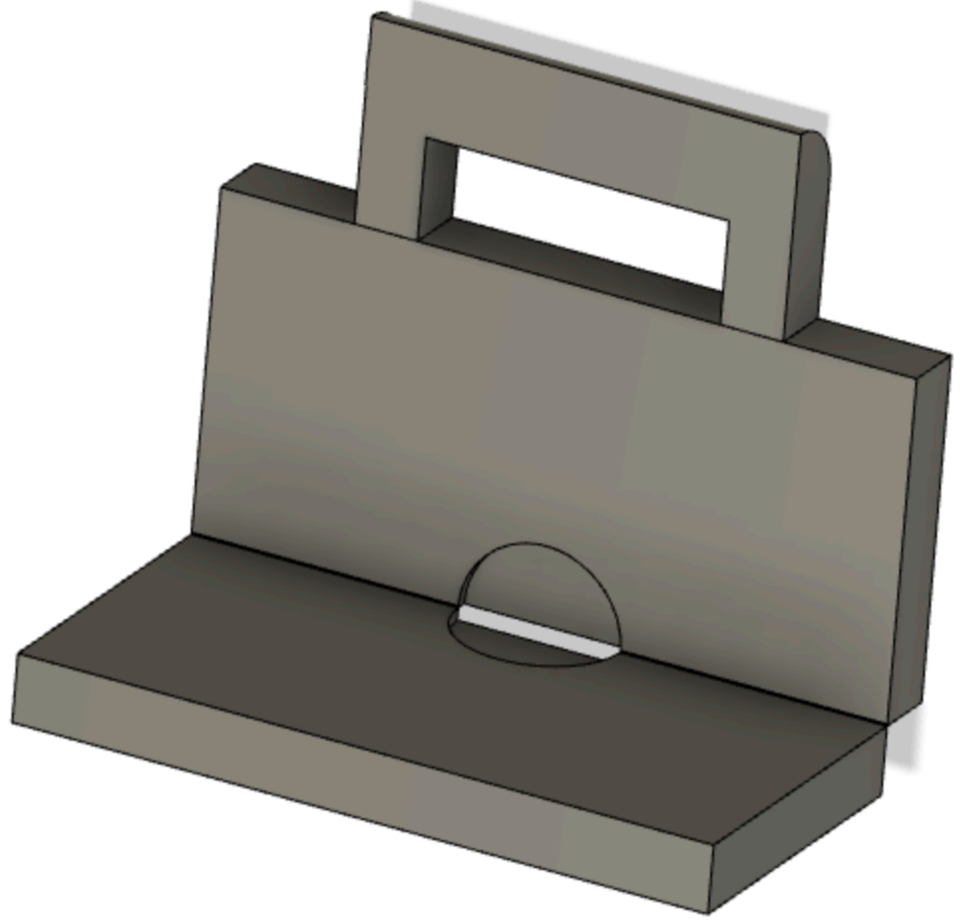


DFM • Requires 2 - 3 components with rigid joints; Easily automated and adaptable for scalability in production

Durability • Downward force keeps quarter inside and eliminates operator safety concern

Cost • Hollow insides lower cost (cheaper manufacturing methods)

Design B

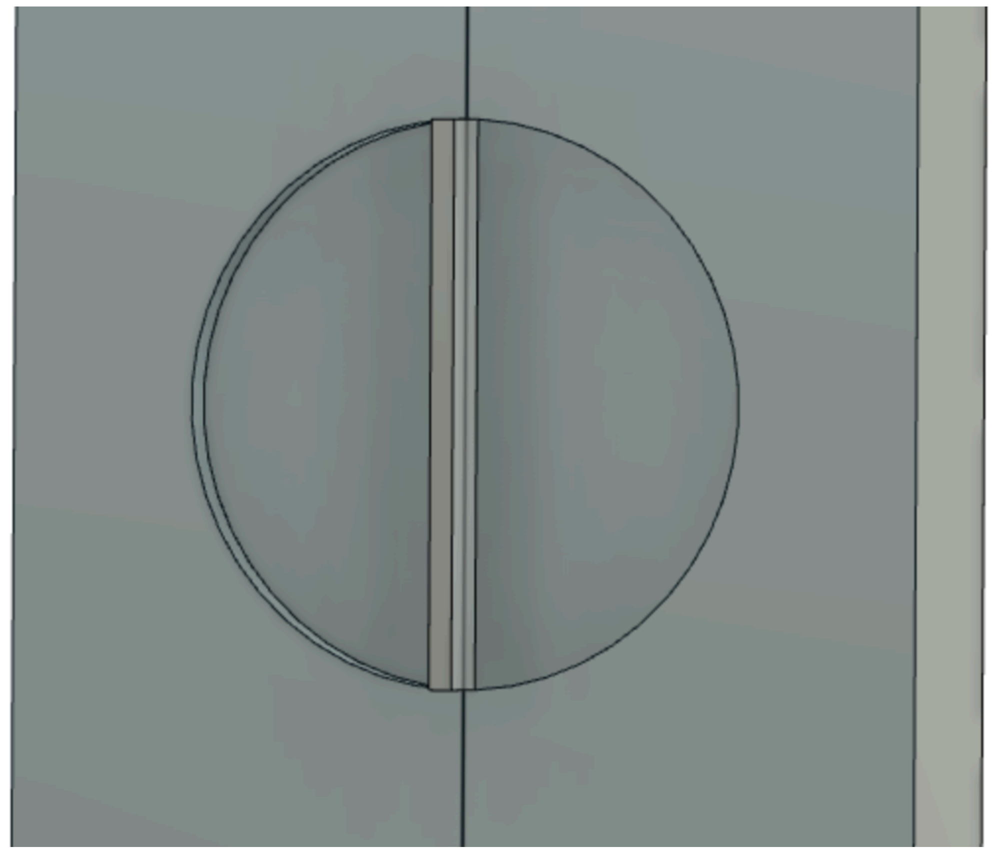


DFM • Requires two separate moving components connected by a hinge joint

Durability • Can become weak at the hinge joint; operator safety concern with quarter flying out during 90° - 180° bend

Cost • Needs multiple materials (i.e. silicone to cover inside to not deface material)

Design C



DFM • Requires two separate moving components separated by a hinge joint; hard to remove quarter after bend

Durability • Multiple moving components could fail or come out of alignment for an unequal quarter bend

Cost • Higher number of components and actuation

Quarter Cross Section

Assumptions

- Bend Radius = 0.25 mm
- $Bend\ Allowance,\ b = \pi \times 0.25\ mm = 0.7854\ mm$
  Cross section does not change across bending action

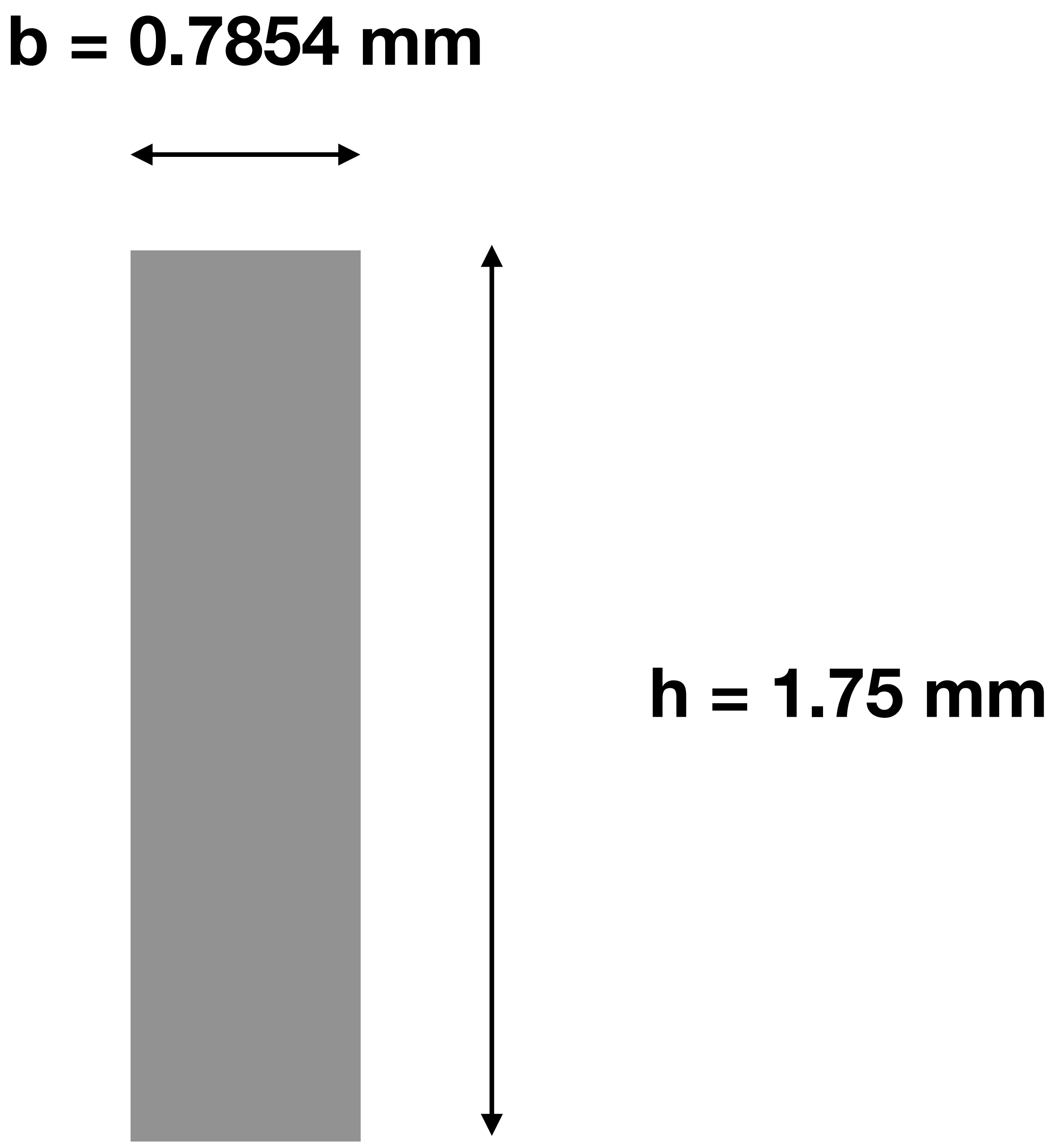
Calculations

$$I = \frac{bh^3}{12} = \frac{(0.79\ mm)(1.75\ mm)^3}{12} = 0.35\ mm^4 = 3.5 \times 10^{-13}\ m^4$$

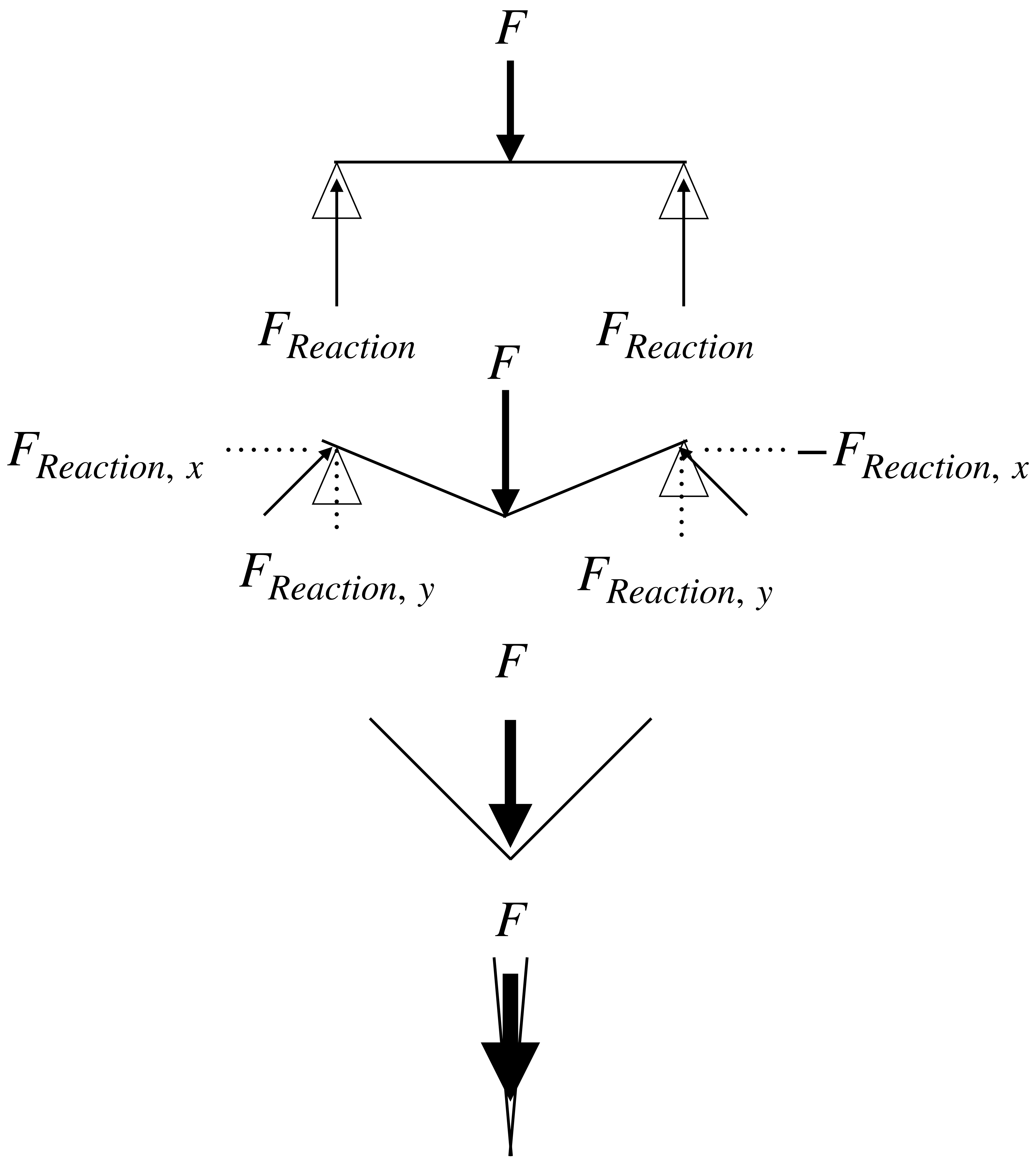
The equation on the right refers to the slope of the ends of the beam as it deflects. Using this equation, we can approximate the force P needed at each stage of the slope, from 0° - 90° (from a horizontal beam, to a fully vertical beam to indicate a full 180° bend).

$$\theta_1 = \theta_2 = \frac{Pl^2}{16EI}$$

Beam Slope Deflection for A Simply Supported Beam



Why Does the Quarter Bend?



Modeling the Quarter As a Simply Supported Beam

1) A simply supported beam means that reactionary forces from the simple supports are normal to the surface of the material being supported.

2) Reaction forces shift to stay normal to face of the material being supported.

$$\Sigma F = F - 2F_{Reaction} = 0 \rightarrow F_{Reaction} = \frac{1}{2}F$$

$$\theta = slope$$

$$\Sigma F_x = \frac{1}{2}F_{Reaction}cos\theta - \frac{1}{2}F_{Reaction}cos\theta = 0 \rightarrow \Sigma F_x = 0$$

$$\Sigma F_y = \frac{1}{2}F_{Reaction}sin\theta + \frac{1}{2}F_{Reaction}sin\theta \rightarrow \Sigma F_y = F_{Reaction}sin\theta$$

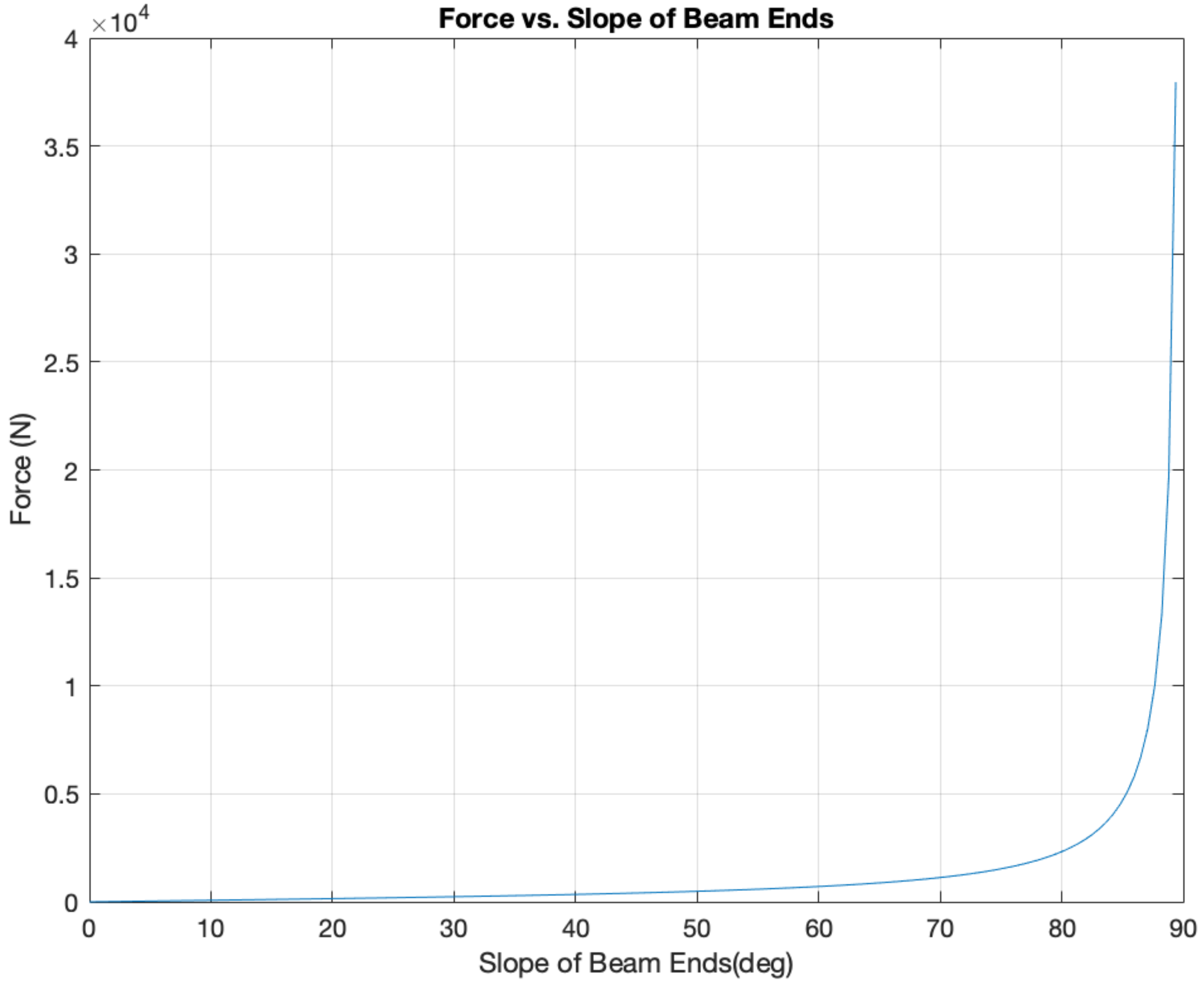
$F > Fsin\theta$, so the sheet metal bends.

The increasingly bolded force arrow indicates an increasing magnitude of applied force.

Forces Through the Bend

Calculations

1. $\theta_1 = \theta_2 = 0^\circ \rightarrow 90^\circ$
2. Solve $\theta_1 = \theta_2 = \dfrac{Pl^2}{16EI}$ for P as output variable



Conclusion

Since it grows exponentially to get the quarter to fully bend to 180° and we are allowed 5° planar offset, I will look at the force needed at 175°. This comes out to be approximately **10040 N** needed to deflect the beam to a ~180° bend.

Bending Stresses

However, to *permanently* bend the plate, we need to exceed the elastic limit of the material. We will need to bend it so the bending stresses exceed the yield strength of the material (NiCu = 275 MPa).

$$\sigma_b = \frac{My}{I}$$

$\sigma_b =$ bending stress
M = calculated bending moment
y = vertical distance away from neutral axis
I = moment of inertia around neutral axis

Solve for force needed to being permanent bending:

$$\sigma_{yield} = \frac{F}{A} \rightarrow F = \sigma_{yield}A \rightarrow F = (105\ GPa)(19\ mm^2) = 1995\ N$$

Solve for M:

$$Bending\ Moment,\ M = (1995\ N \times 0.01213\ m) = 24.2\ Nm$$

$$\sigma_b = \frac{My}{I} = \frac{24.2\ Nm \times 0.875 \times 10^{-3}\ m}{3.5 \times 10^{-13}\ m^4} = 6.05 \times 10^{10}\ Pa$$

As is confirmed, σ_b at 1995 N became greater than the σ_{yield}, which is why permanent deformation began.

Sheet Metal Bending

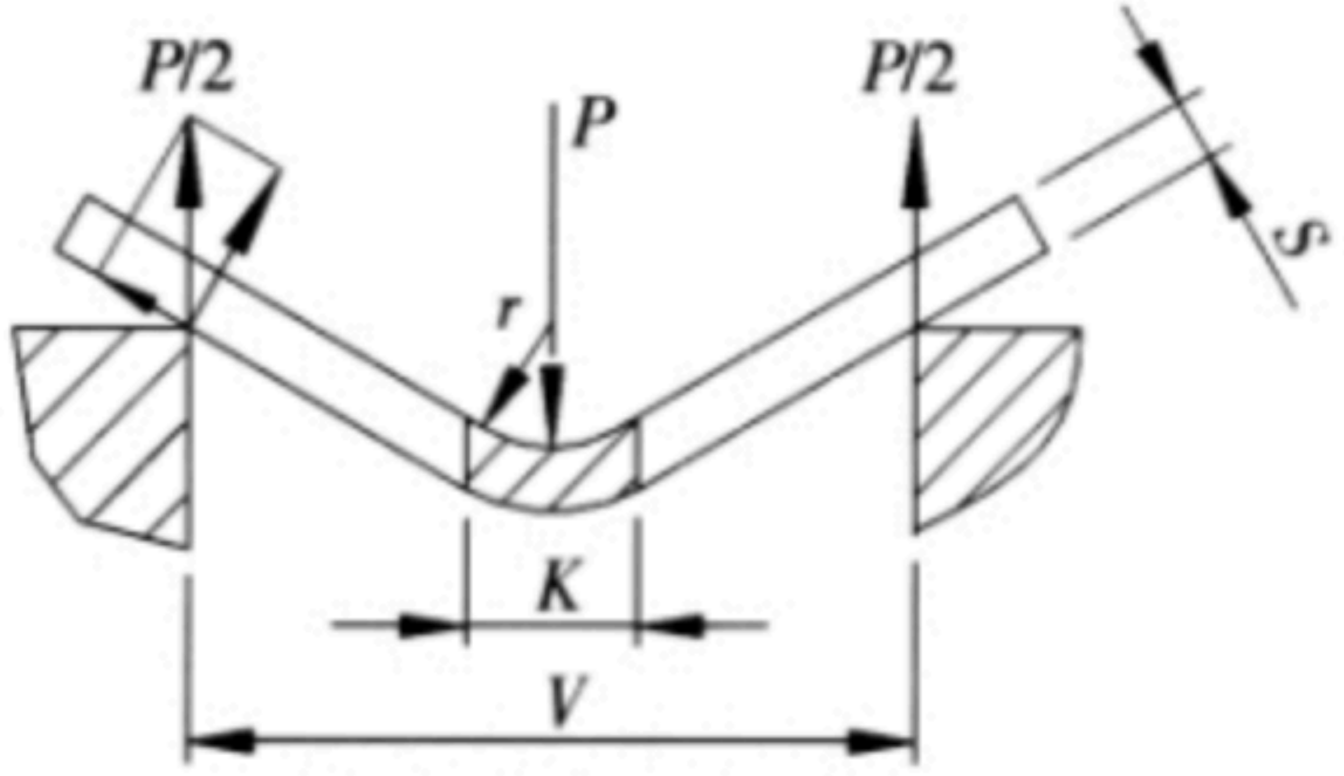


Figure 1 Bending diagram

- P-bending force
- S-sheet thickness
- V-lower die opening width
- r-Inner radius when the sheet is bent
- K-the width of the horizontal projection of the bending deformation zone

https://www.machinemfg.com/calculation-of-sheet-metal-bending-force-in-air-bending/

Types of Die Bending

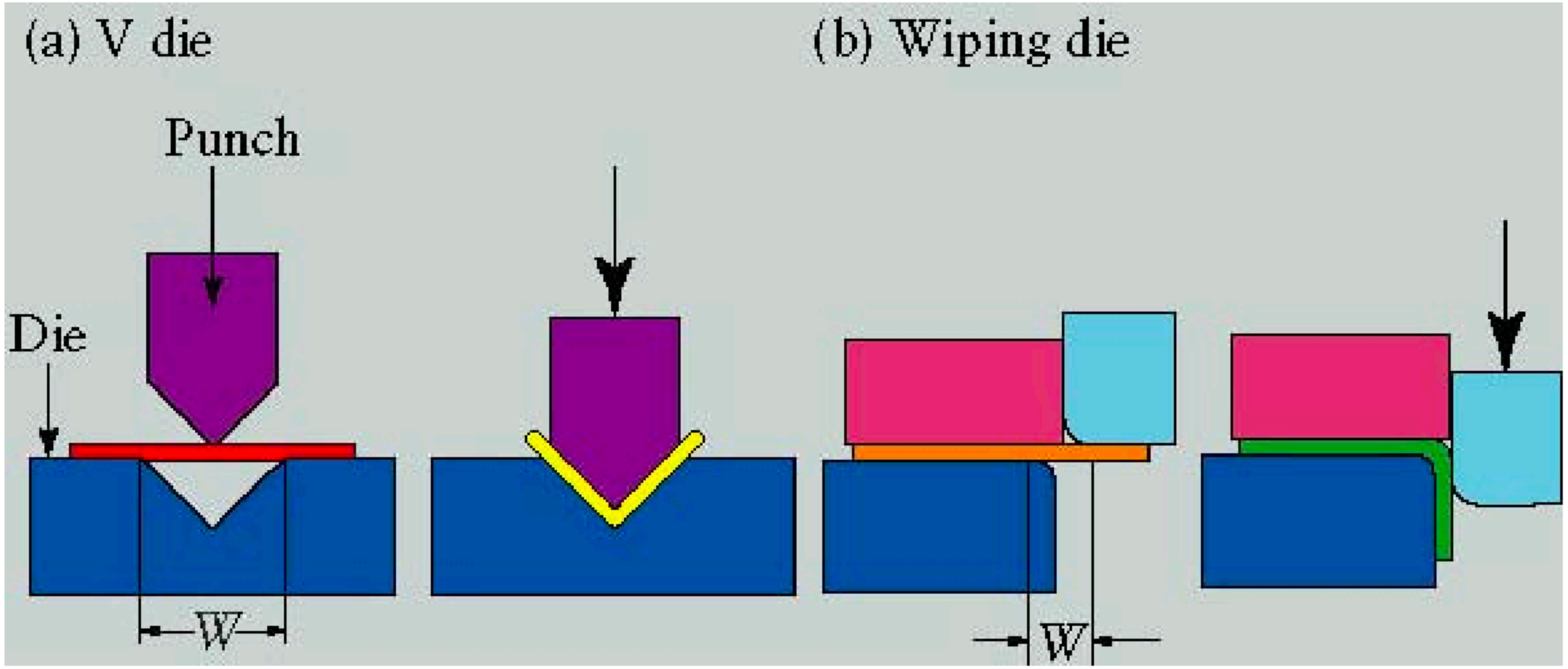


Figure 2: Common Die-Bending Operations

http://kaizenha.com/cdn/files/Manufacturing%201/Lecture%2015.pdf

Maximum Bending Force (V-Die)

Calculations

- k = 1.33 (v-bending)
- TS = 275 MPa (Cu-Ni)
- t = 1.75 mm (quarter's thickness)
- w = 24.26 mm
- D = 12 mm

Thus, F = 2265 N

Bending Force

Maximum bending force estimated as follows:

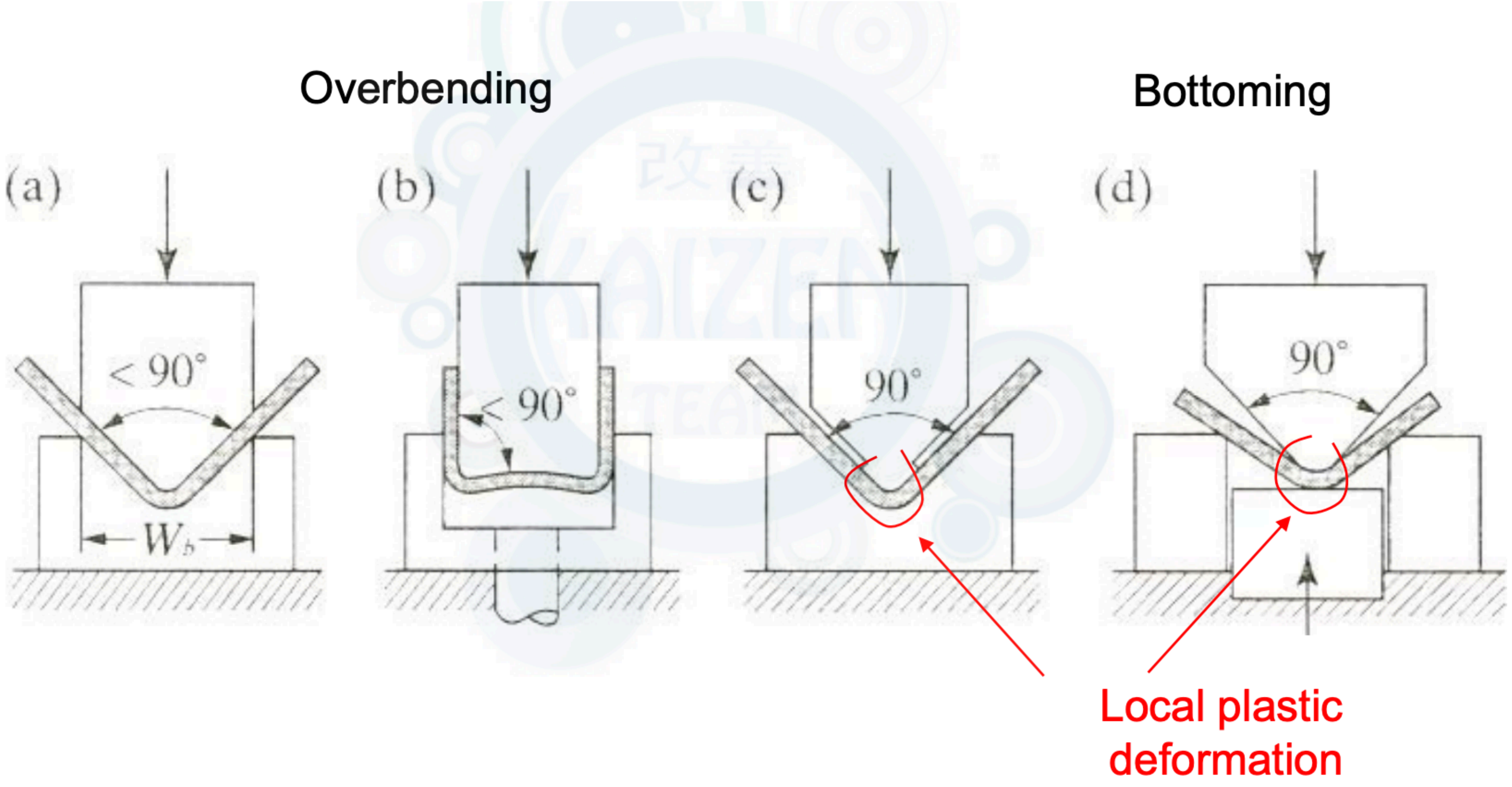
$$F = \frac{K_{bf} TS w t^2}{D}$$

where F = bending force; TS = tensile strength of sheet metal; w = part width in direction of bend axis; and t = stock thickness. For V- bending, K_{bf} = 1.33; for edge bending, K_{bf} = 0.33

http://www.tthk.ee/inlearcs/4-bending-technology/

Compensation for Spring Back

- Over-bending of part
- Bottoming Punch: Subject bend area by subjecting it to high localized compression between tip of punch and the die surface
- Stretch Bending: Part is subjected to tension during bending; to reduce spring back, bending can be carried out at elevated temperatures



http://kaizenha.com/cdn/files/Manufacturing%201/Lecture%2015.pdf

Blade Material: Hardened Steel

Calculations

F = 2265 N
A = 0.7854 mm * 24.26 mm = 19 mm^2

σ = F / A = 120 MPa

Properties

- Resistant to wear, rough usage, high-impact pressure, shock
- Resistant to corrosive chemical environments, water, atmospheric corrosion
- Exceptional resistance to severe sliding abrasion and can withstand drilling / punching
- Durability of heat-treated hardened steel is 2x that of untreated and oil-treated steel
- Examples: ATS34, Sandvic 12C27, Z60CDV14

Mechanical Properties

Hardness, Knoop	555	555	Converted from Vickers hardness.
Hardness, Vickers	531	531	
Tensile Strength, Ultimate	1855 MPa	269000 psi	
Tensile Strength, Yield	1550 MPa	225000 psi	
Elongation at Break	12 %	12 %	
Reduction of Area	40 %	40 %	
Modulus of Elasticity	196 GPa	28400 ksi	
Bulk Modulus	140 GPa	20300 ksi	Typical for steel.
Poisson's Ratio	0.3	0.3	Calculated
Machinability	50 %	50 %	annealed and cold drawn. Based on 100% machinability for AISI 1212 steel.
Shear Modulus	75 GPa	10900 ksi	Estimated from elastic modulus

AISI 4000 Steel Properties

https://sciencing.com/properties-hardened-steel-6301296.html

Hardened Steel Stress-Strain Curves

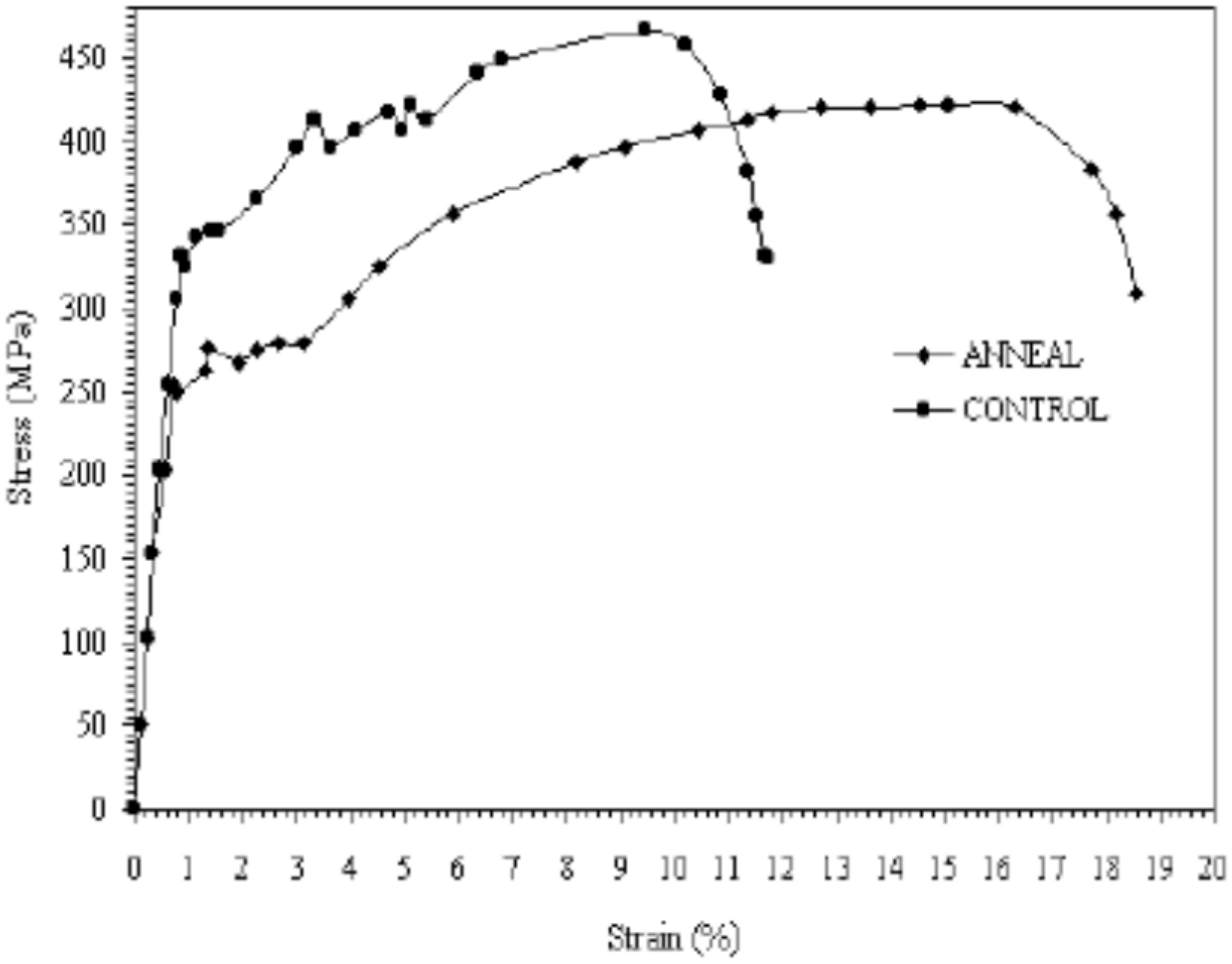


Figure 2: Stress versus strain curve for annealed and control specimens

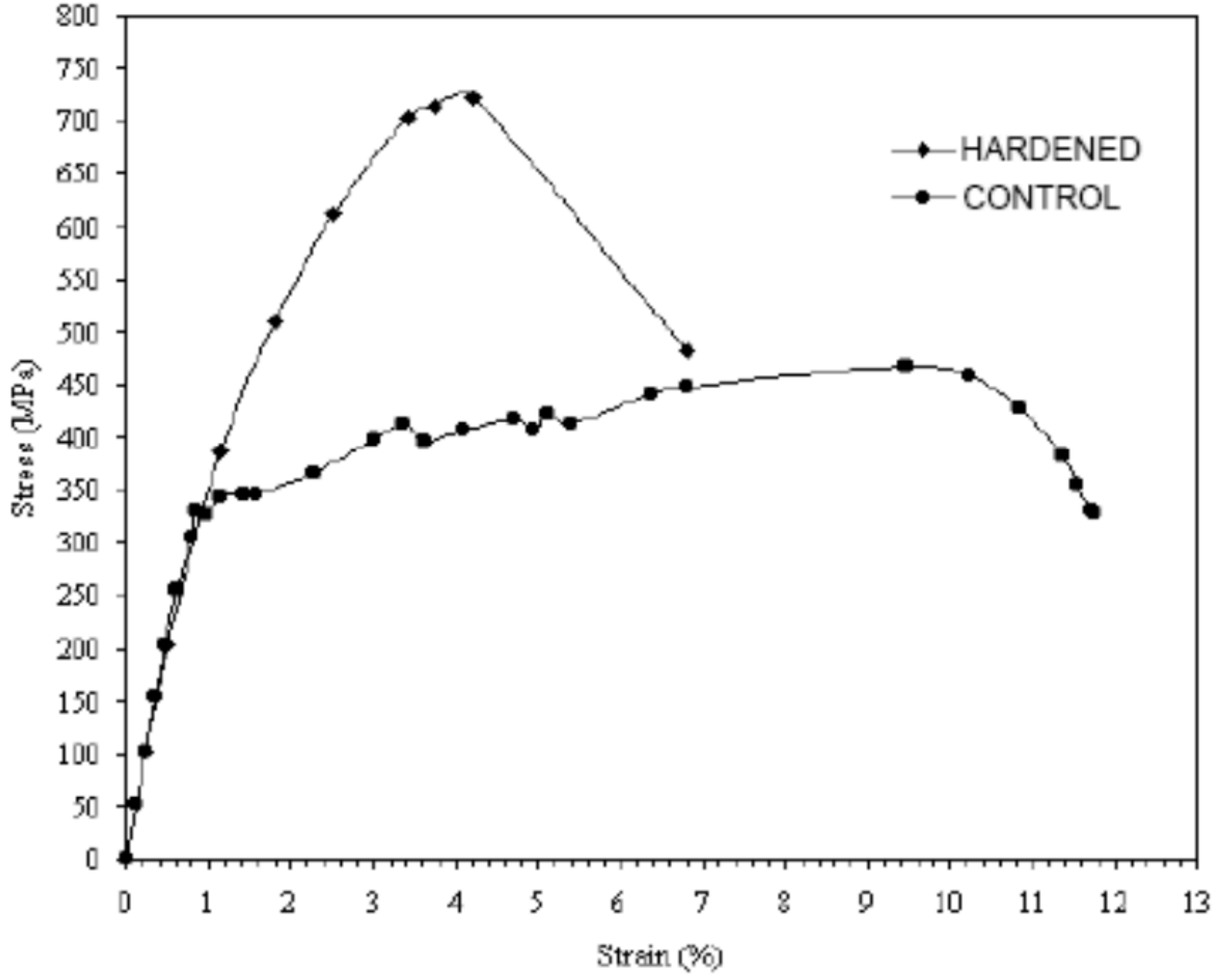
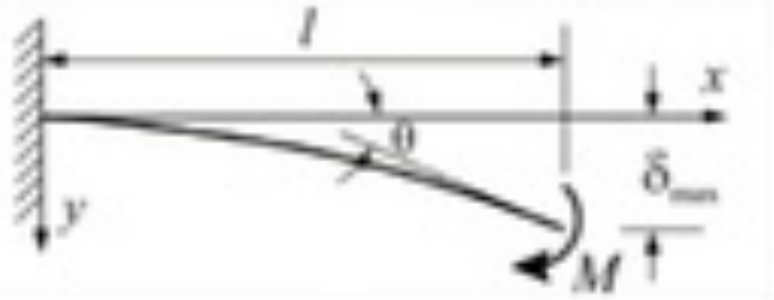
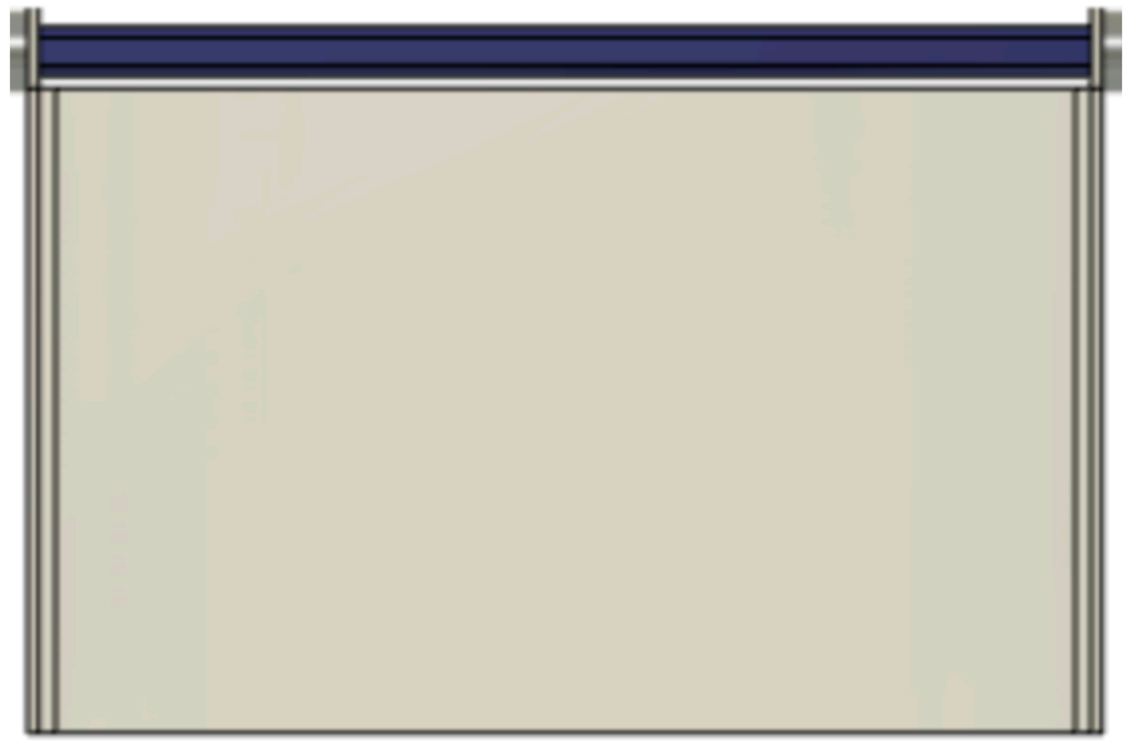


Figure 5: Stress versus strain curve for hardened (water quench) and control specimens

Blade Design

5. Cantilever Beam – Couple moment M at the free end			
	$\theta = \frac{Ml}{EI}$	$y = \frac{Mx^2}{2EI}$	$\delta_{max} = \frac{Ml^2}{2EI}$



To reduce deflection:
- Reduce length
- Increase Modulus of Elasticity
- Increase Moment of Inertia
    - Increase height of x-section
    - Increase width of x-section
    - Reduce moment on beam end

Properties
- 0.5 mm-wide blade with flanges to accommodate for bent quarter and less material where bending stress is low (middle)

Cupronickel Fabrication

- Hot working temperature range: 800 ˚C - 900 ˚C
- Stress Relief Heat Treatment
  - Full annealing: 700 ˚C - 800 ˚C
  - Dependent on extent of cold work, section thickness, annealed temper, grain size

https://www.nickelinstitute.org/media/1650/copper_nickelalloys_propertiesandapplications_12007_.pdf

Metal Heat Treatments

- Metal Hardening: Heated above critical transformation temperature of material, then cooled rapidly enough to cause soft initial material to transform to a much harder, stronger structure

- Metal Quenching: Heated up to suitable temperature, then quenched in water or oil to harden to full hardness.

- Metal Tempering: Treatment follows quenching or air cooling operation. Effective in 1) relieving stresses from quenching, 2) lowering hardness to a specific range, 3) meeting certain mechanical property requirements

https://www.metlabheattreat.com/metal-hardening-metal-quenching-metal-tempering.html

Reducing Cracks Along Seam: Stress Relieving

- Reduce or eliminate residual stress and reduces likelihood that part will fail by cracking or corrosion fatigue

- Parts are stress-relieved at temperatures below annealing range (in cupronickel's case, 700 ˚C - 800 ˚C) to not cause recrystallization and softening of metal

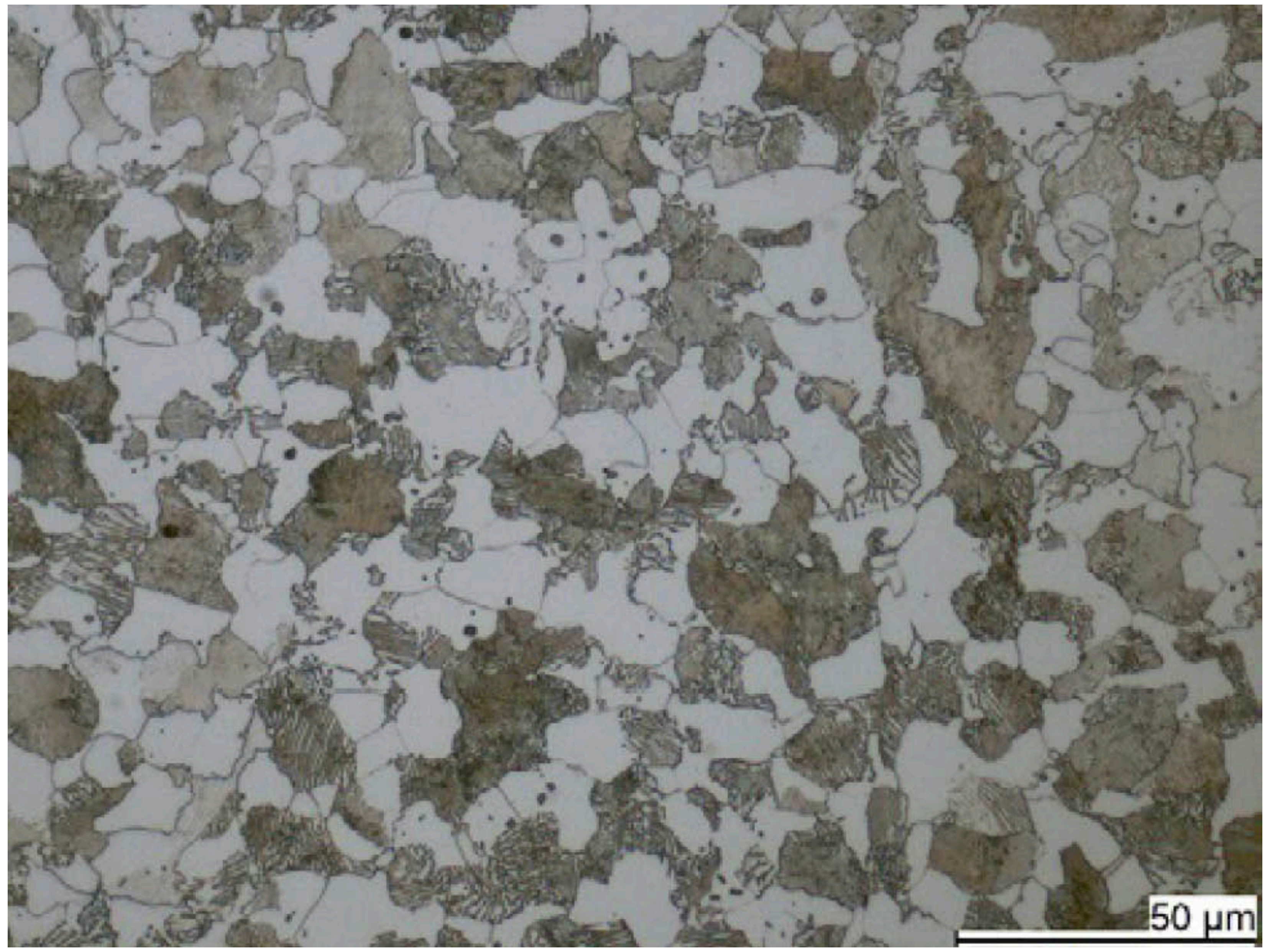
- Goal: use high stress-relieving temperature for a short time, which will result in some sacrifice in mechanical properties

https://www.totalmateria.com/page.aspx?ID=CheckArticle&site=ktn&NM=25

Tracking Material Changes: Spectroscopy

Overview

- Microstructural analysis helps draw conclusions on properties of alloy (strength, hardness, ductility, etc.)
- Microstructures can only be assessed by microscope (stereo microscope, light microscope using reflected light, digital microscope, scanning and transmission electron microscope
- Useful during manufacturing process to check for changes in material during material heating and cooling

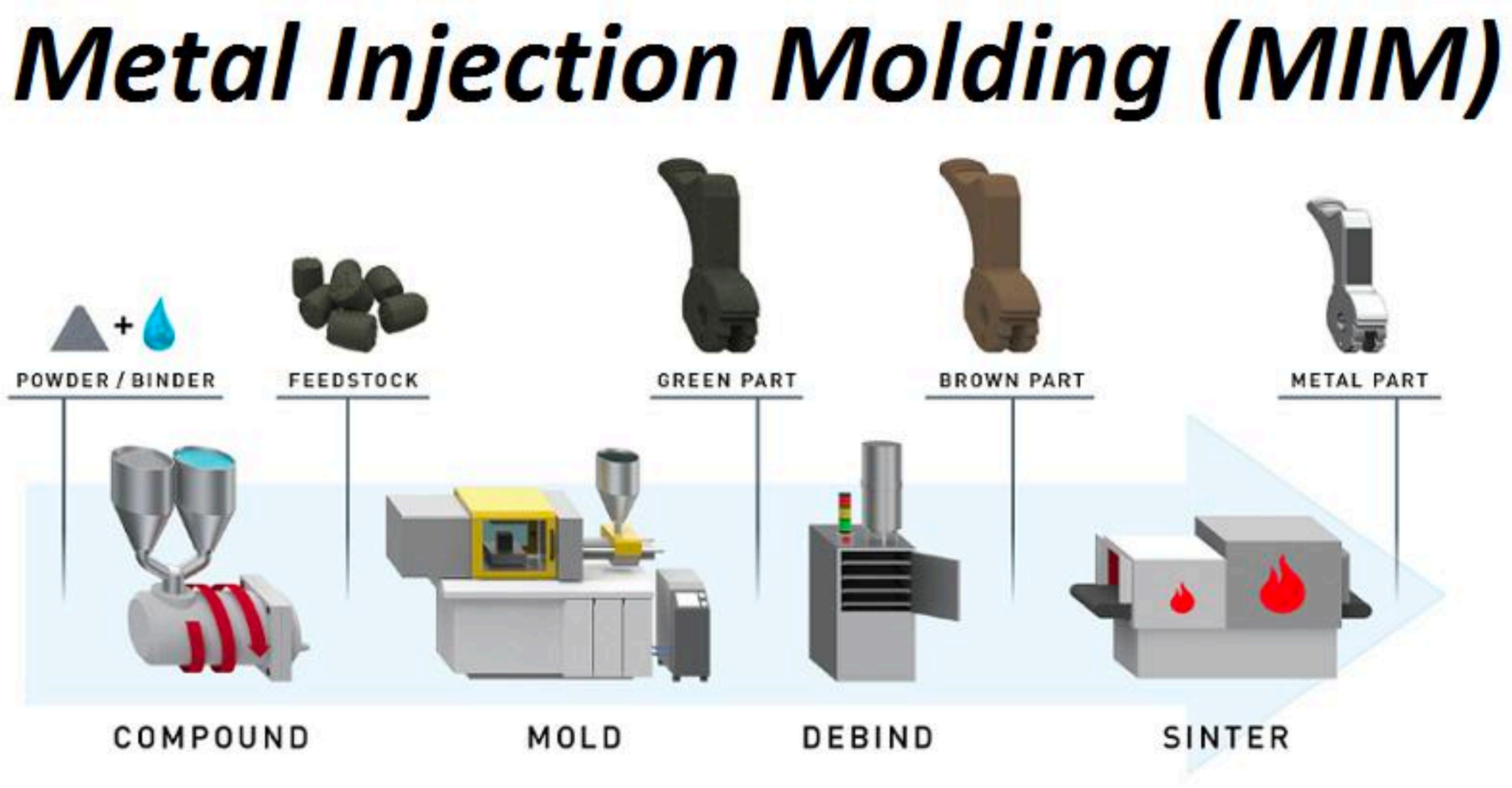


Ferritic-pearlitic steel with ~ 0.2% C, etched with Nital

Metal Injection Molding

Overview

- Repeatable process for complex components made from high-temperature alloys (good for blade material)
- MIM parts are nearly fully dense, thus retaining needed mechanical, corrosion, and thermal properties



Design Criteria

- Corner breaks: > 0.005” radius
- Draft angles
- No sudden variances in thicknesses

https://facfox.com/wp-content/uploads/2019/08/MIM_Design_Guide.pdf

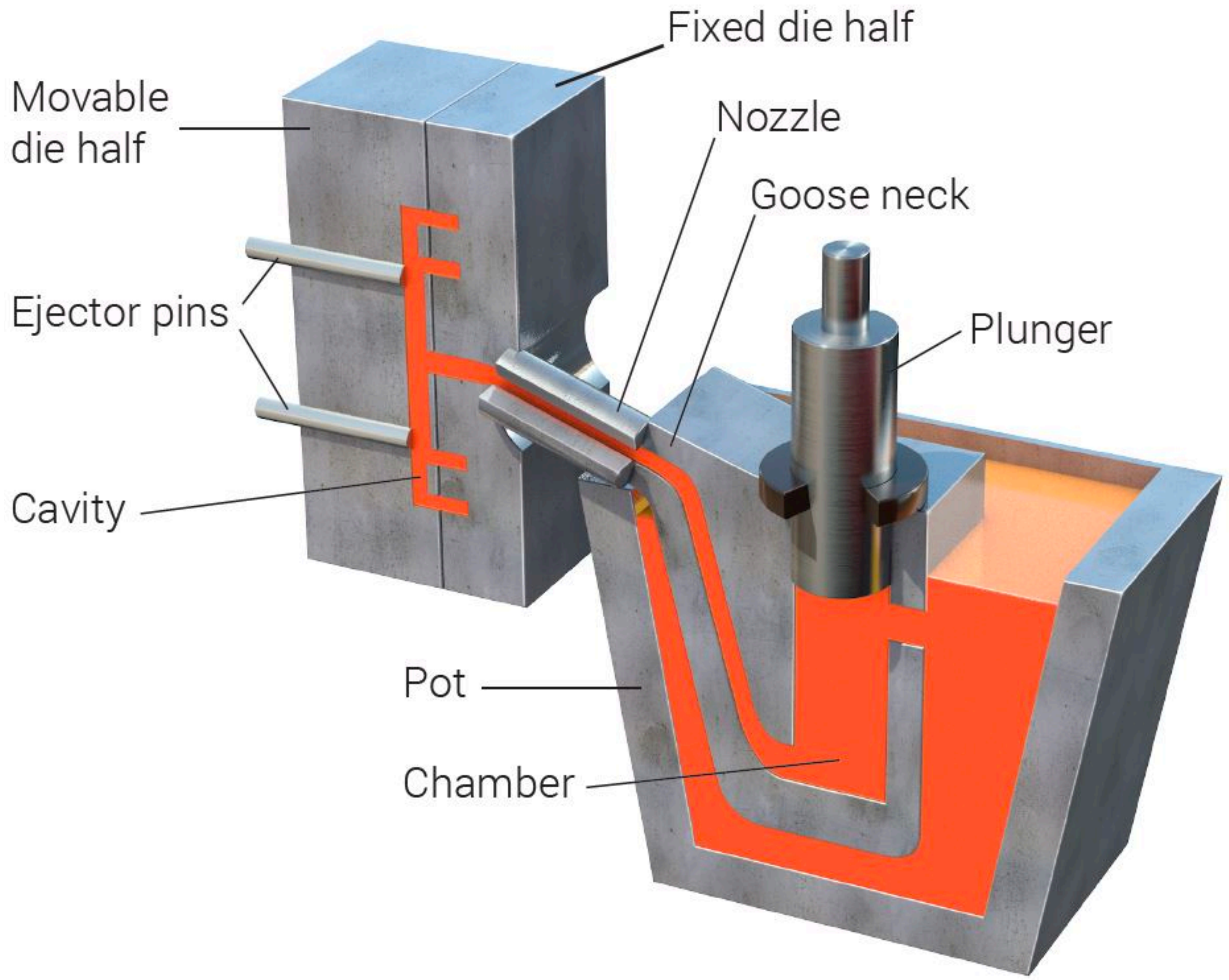
Die Casting

Overview

- Metal casting process that forces molten metal under high pressure into mold cavity
- Good for tighter tolerances
- Faster production cycle and lower cost
- Usually non-ferrous metals such as aluminum, zinc, or magnesium

Design Criteria

- Decrease maximum wall thickness
- Uniform wall thickness
- Rounded corners to reduce stress concentration and fractures
- Draft angles parallel to parting direction
- Minimize undercuts



https://www.custompartnet.com/wu/die-casting

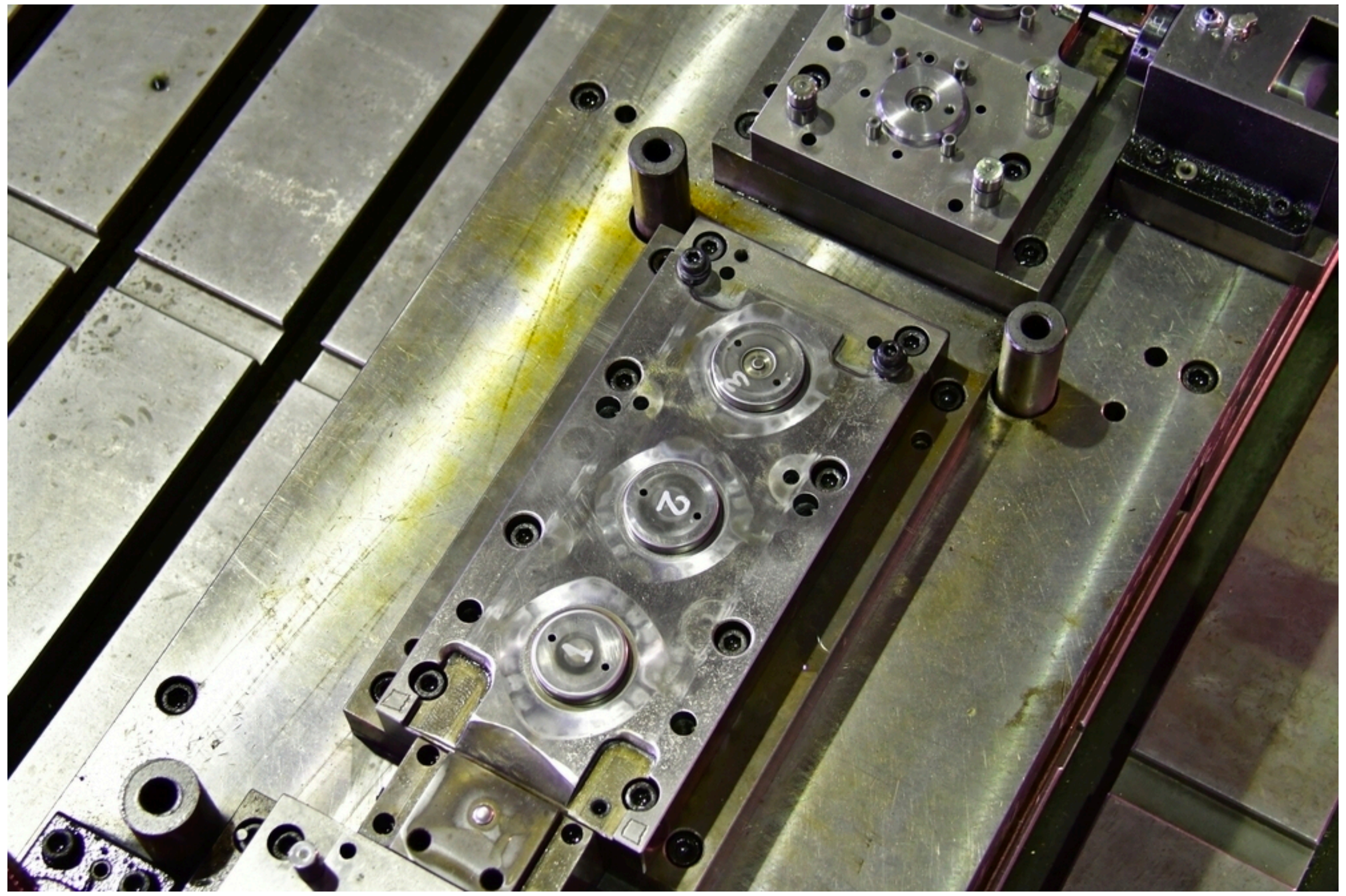
Metal Stamping

Overview

- Low-cost, high speed manufacturing process for high volume of identical manufacturing components
- Techniques: punching, blanking, embossing, coining, bending, flanging
- Steel rule dies (knife dies): dies for application in cutting and shaping of metals like aluminum, copper, brass

Design Criteria

- Based on use of existing dies for standards shapes and tools
- Avoidance of sharp internal and external corners to reduce potential for large burrs and secondary post-machining operations
- Dimensions limited by available dimensions of metal sheets



https://www.thomasnet.com/articles/custom-manufacturing-fabricating/understanding-metal-stamping/

Proposed Manufacturing Methods

Component	Manufacturing Methods	Reasoning
Quarter Holder Body (2)	Die Casting	Hollow insides allow die casting. Some post-machining may be done for side flanges.
Steel Bottom Plate	Metal Stamping	Rectangular uniform shape with holes punched out lends to a cheaper process with metal stamping.
Blade	Metal Injection Molding	Do not want weakened areas as a result of welding joints between sides and blade.

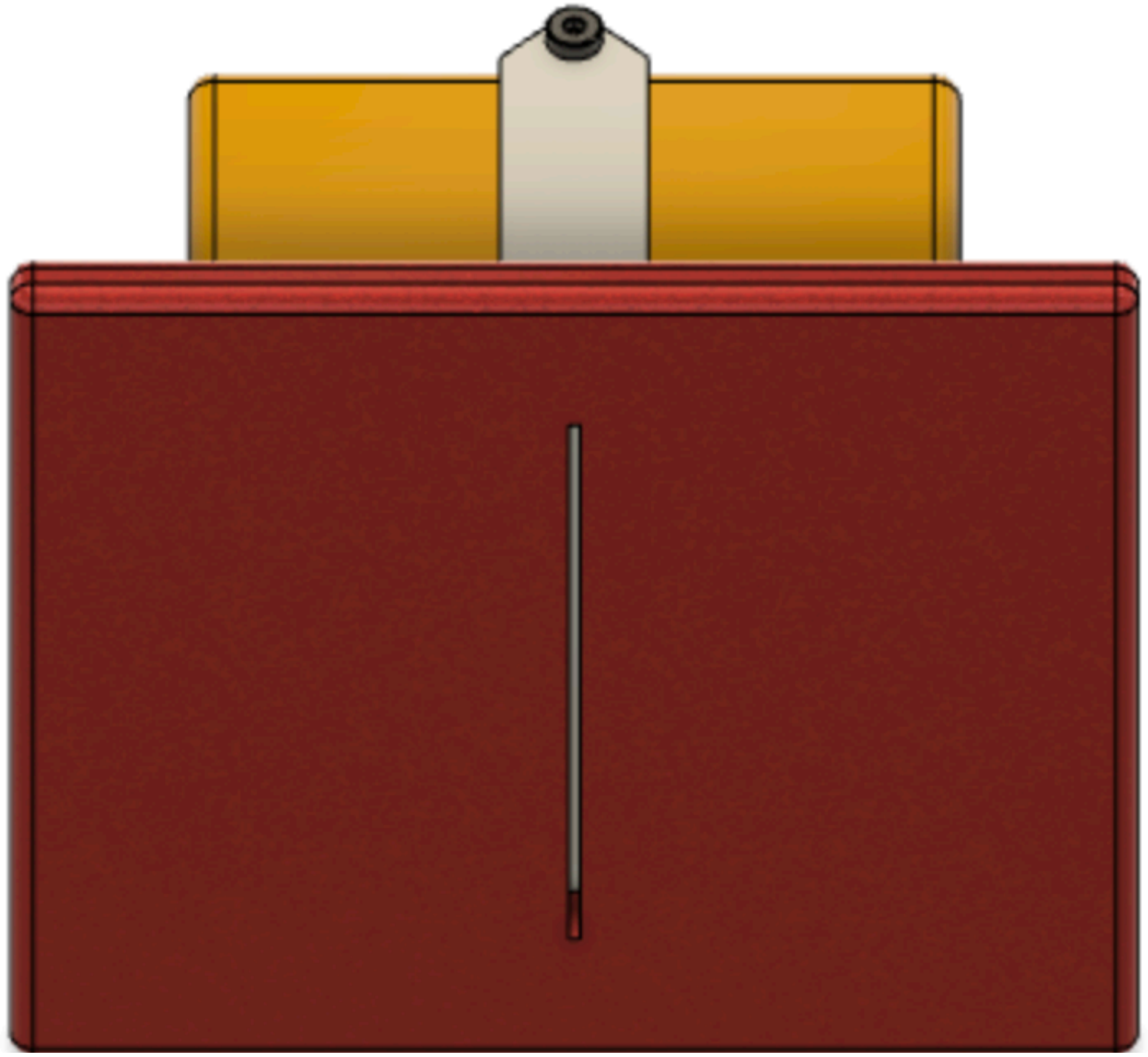
Manufacturing Scalability

- One single motion of actuation in the y-direction leads to easy adoption for automation

- Flat bottom allows it to be placed on top of the opening of a vice to drop straight in and be completely bent for good measure

- An open bottom allows it to be part of a manufacturing process

  - Example: Press quarter through the hole into a bin where it will be brought to another manufacturing process to be completely bent



View of Opening on Bottom

References