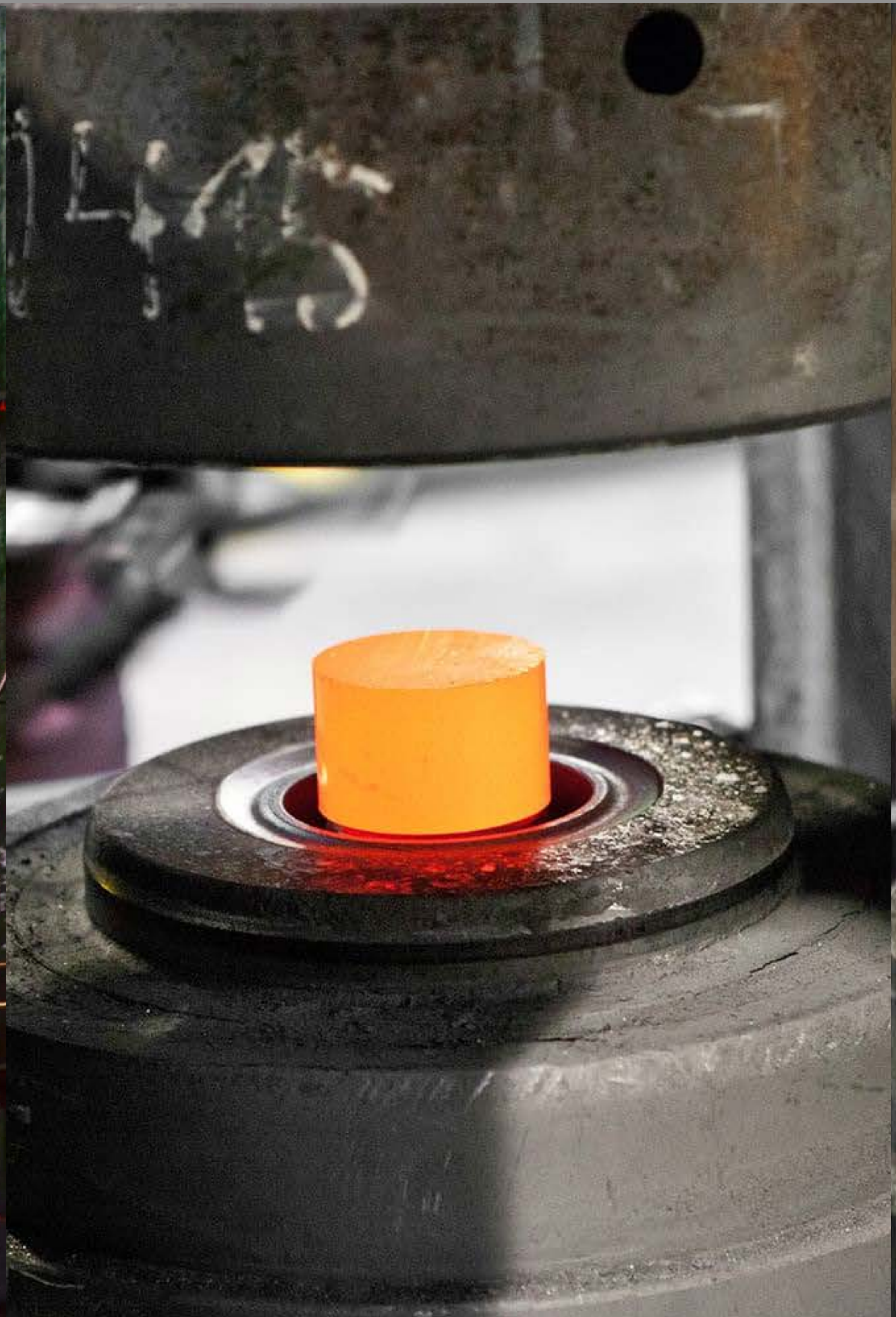
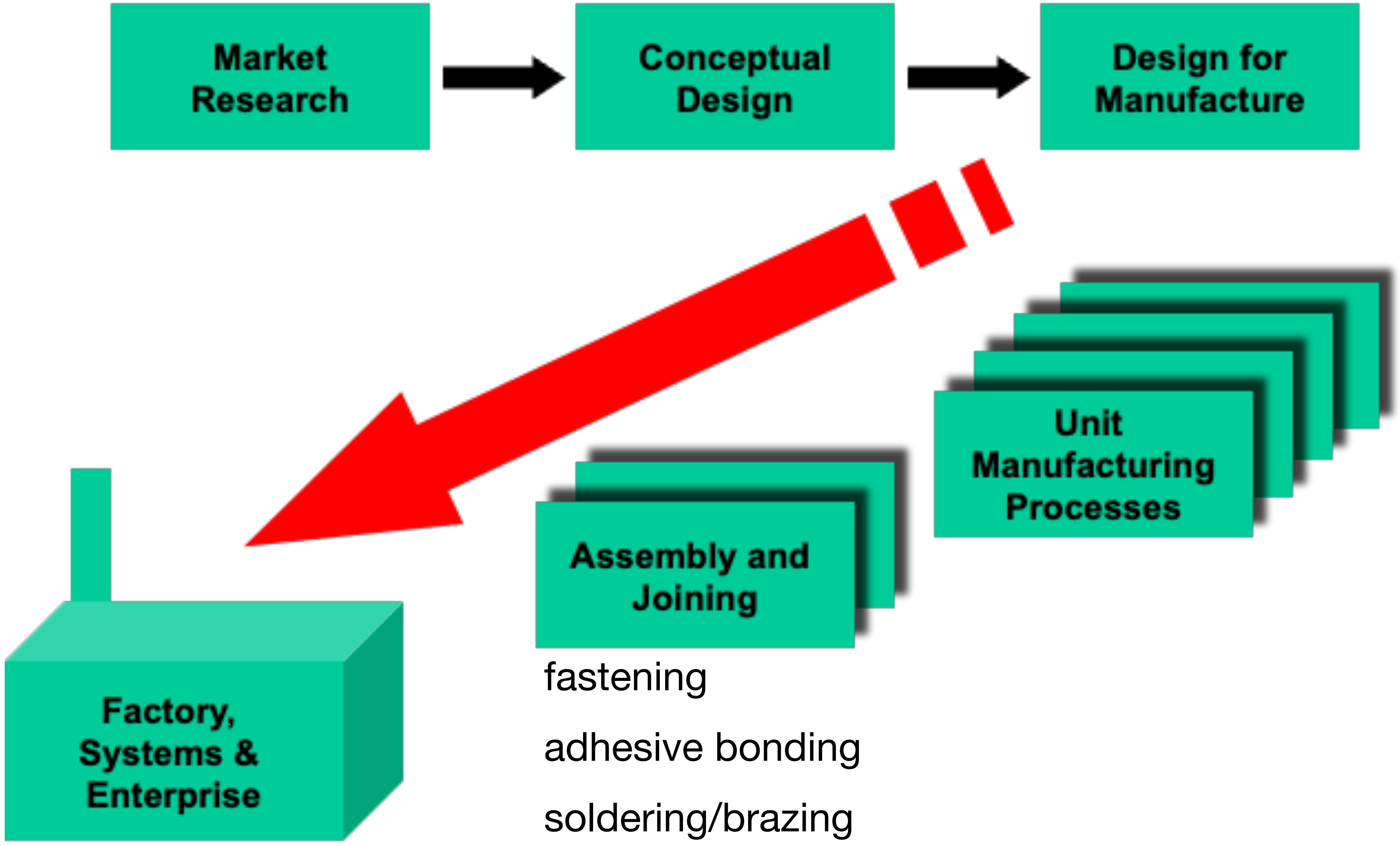
Deforming

Forging, Extrusion, Sheet Metal: Processes and Equipment



Deforming

Forging, Extrusion, Sheet Metal: Processes and Equipment



fastening
adhesive bonding
soldering/brazing
diffusion bonding
fusion welding

injection molding
thermoforming
machining
+ more

variation
quality

2.008 Topic Coverage

Deformation process characteristics

Deformation physics

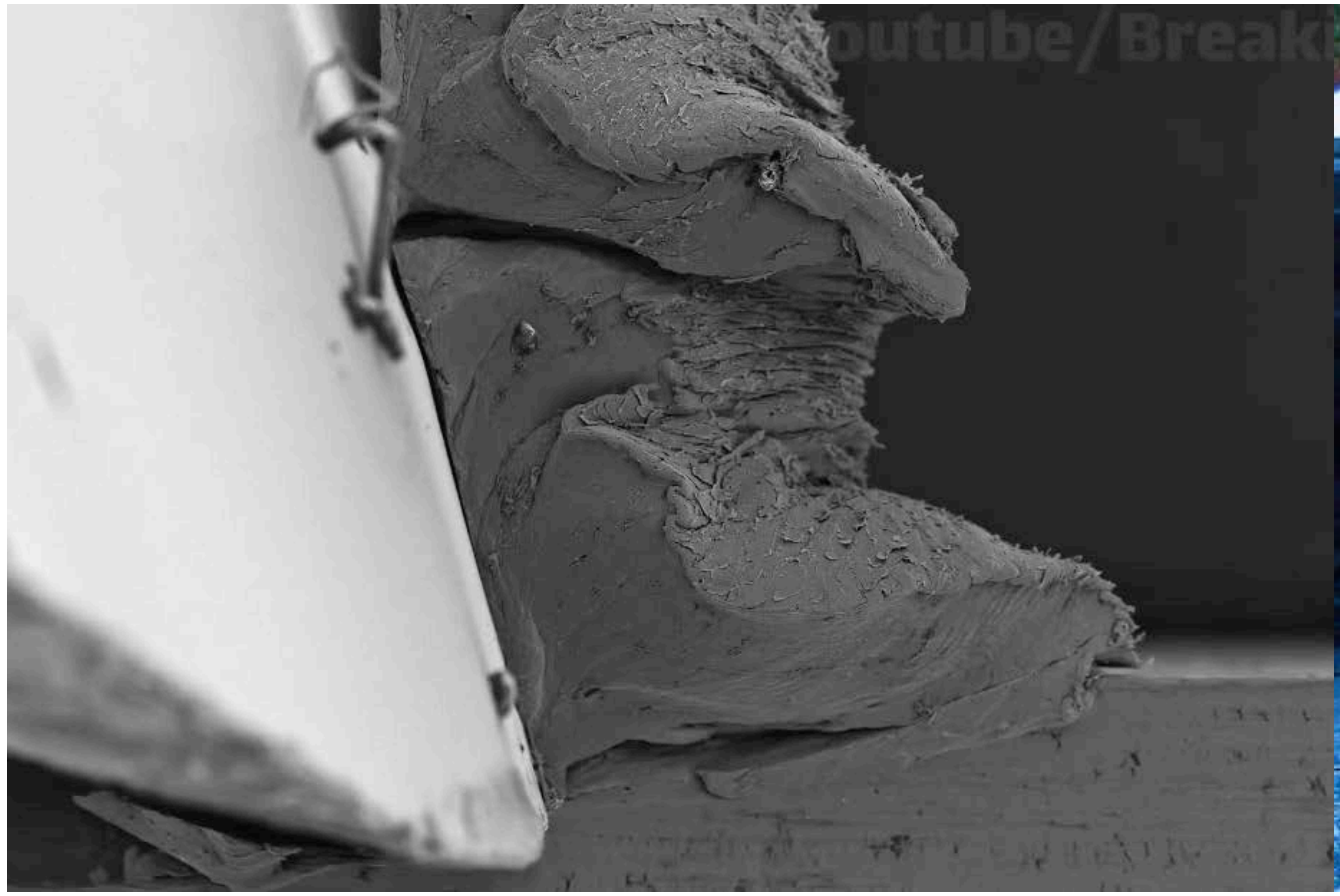
Common deformation processes

DFM

Deforming

Forging, Extrusion, Sheet Metal: Processes and Equipment

Deforming vs Machining



- any ductile material
- shape: limited by strain/plastic flow characteristics
- size: limited by equipment

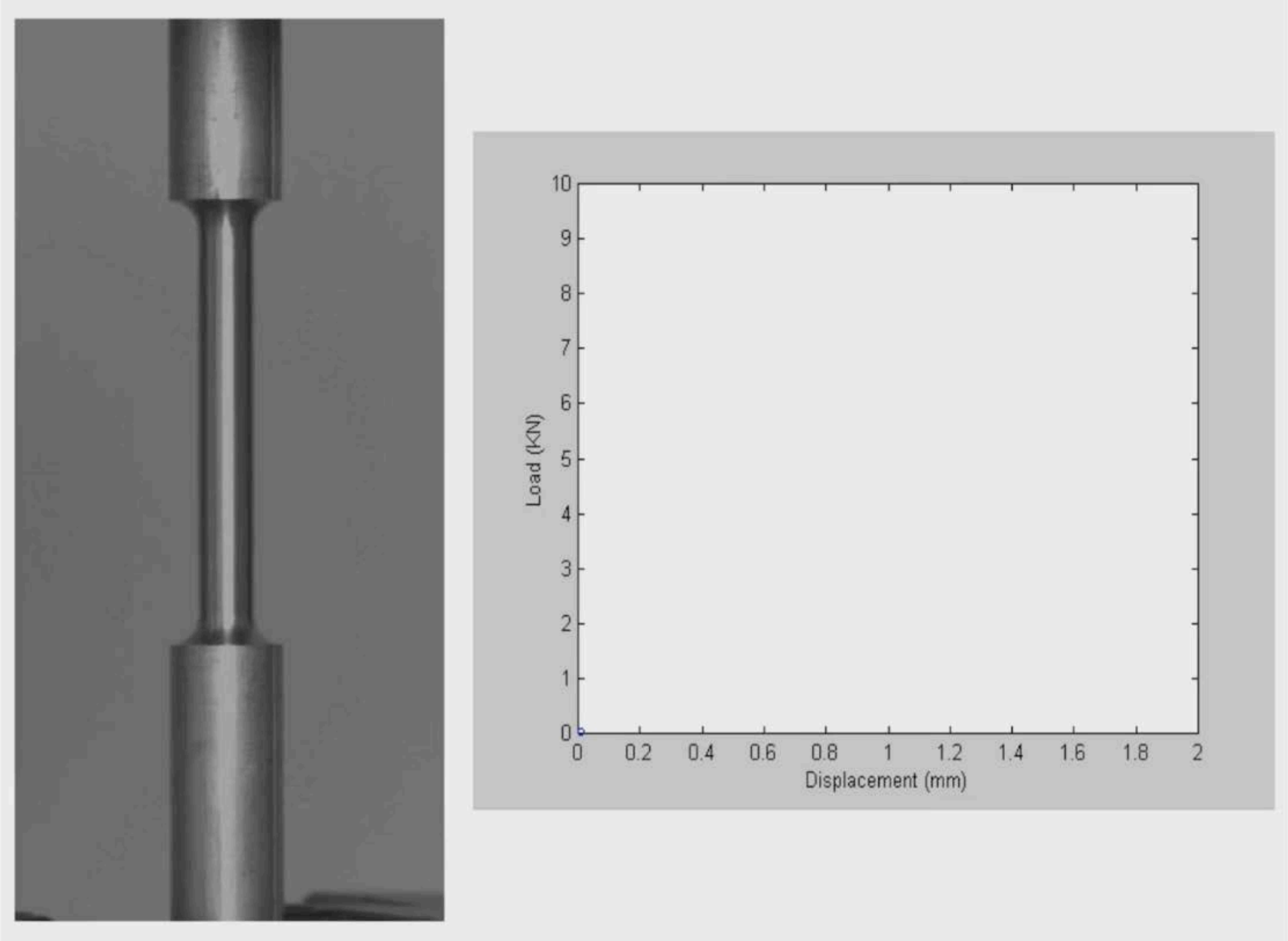
Machining:

- 10s-100s of **lbs**
- concentrated shear zone: break material

Deforming:

- 10s-100s of **tons**
- across large volumes: do not want separation (cracks)

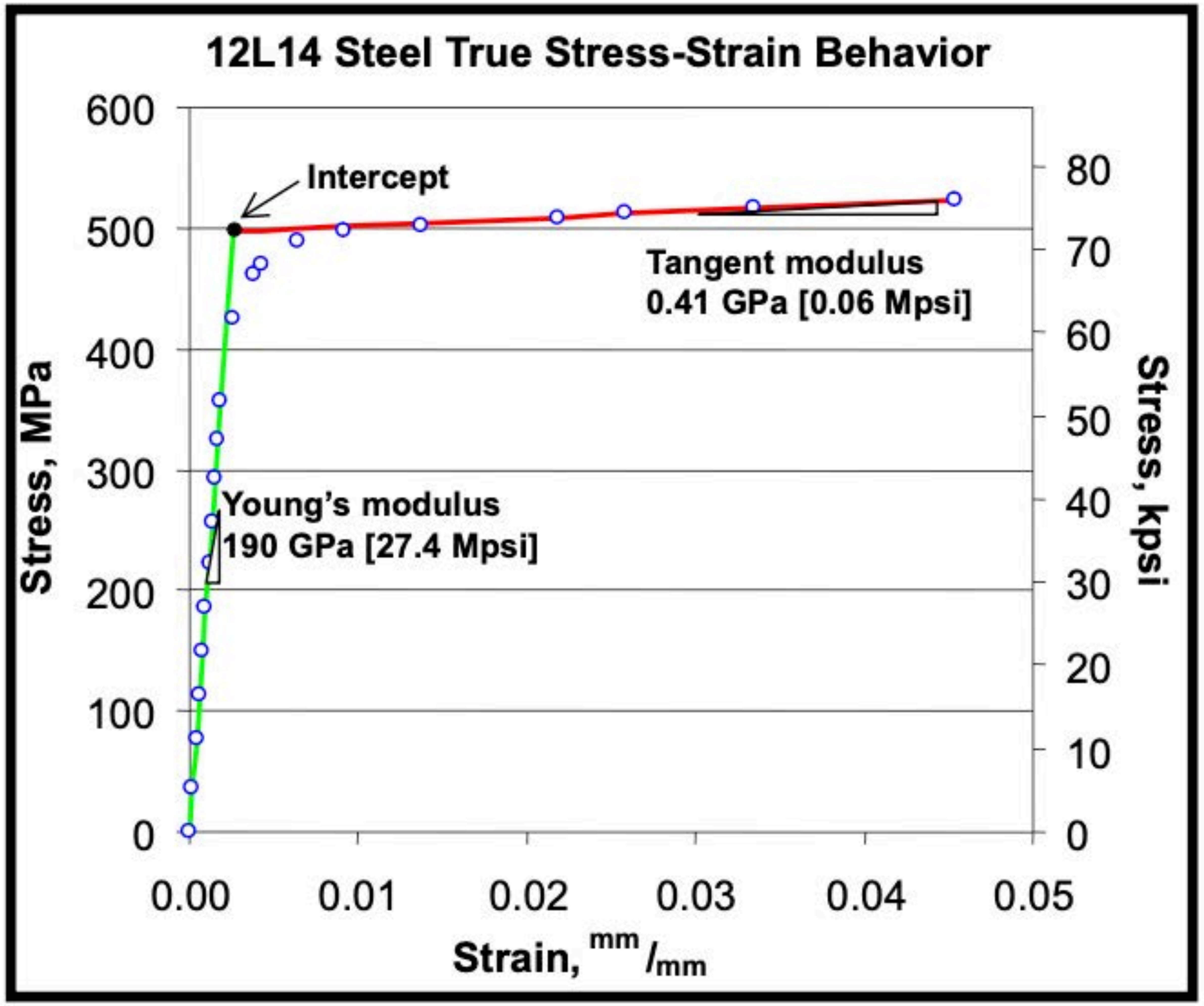
Tensile Testing: Al 6061



Steel: 12L14

elastic → plastic deformation to form part

- we **do not want** elastic - that undoes our work!
- bulk deformation: forging/rolling/extrusion - so much plastic deformation that elastic is not significant
- sheet forming: plastic deformation is not much bigger than elastic
- elevated temperature: easier to deform

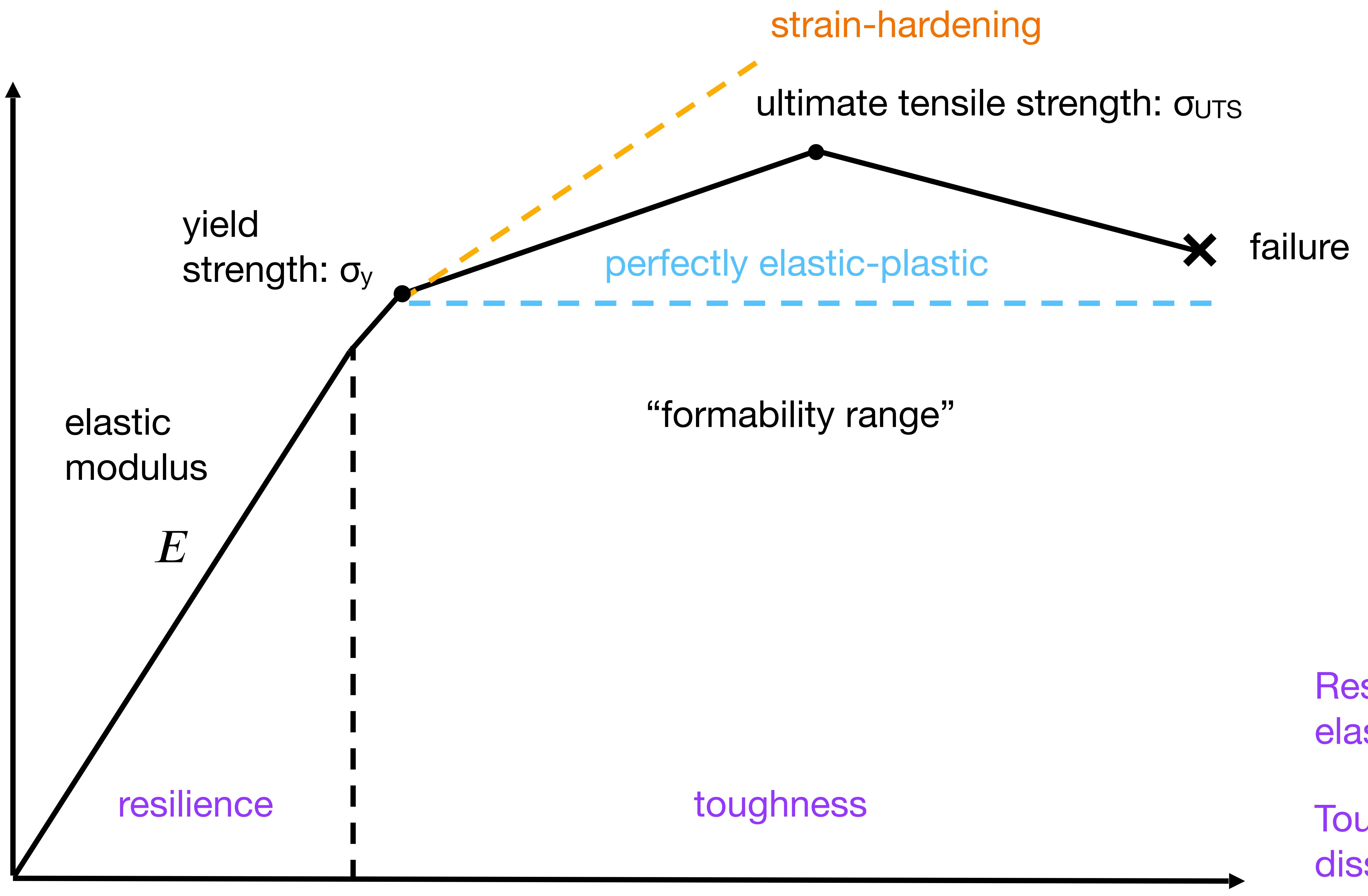


Stress-Strain Curve++

Hooke's Law

$\sigma = E\epsilon$

$\sigma = stress$



$\epsilon = strain$

Resilience: total energy that can be stored elastically

Toughness: total energy that can be dissipated plastically

2.008 Attributes

Internalize the rate, quality, cost, and flexibility as manufacturing attributes

Apply physics to understand the factors that influence the rate, quality, cost, and flexibility of processes

Apply an understanding of variation to the factor that influence rate, quality, cost, and flexibility of processes and systems

Understand the impact of manufacturing constraints on product design and process planning

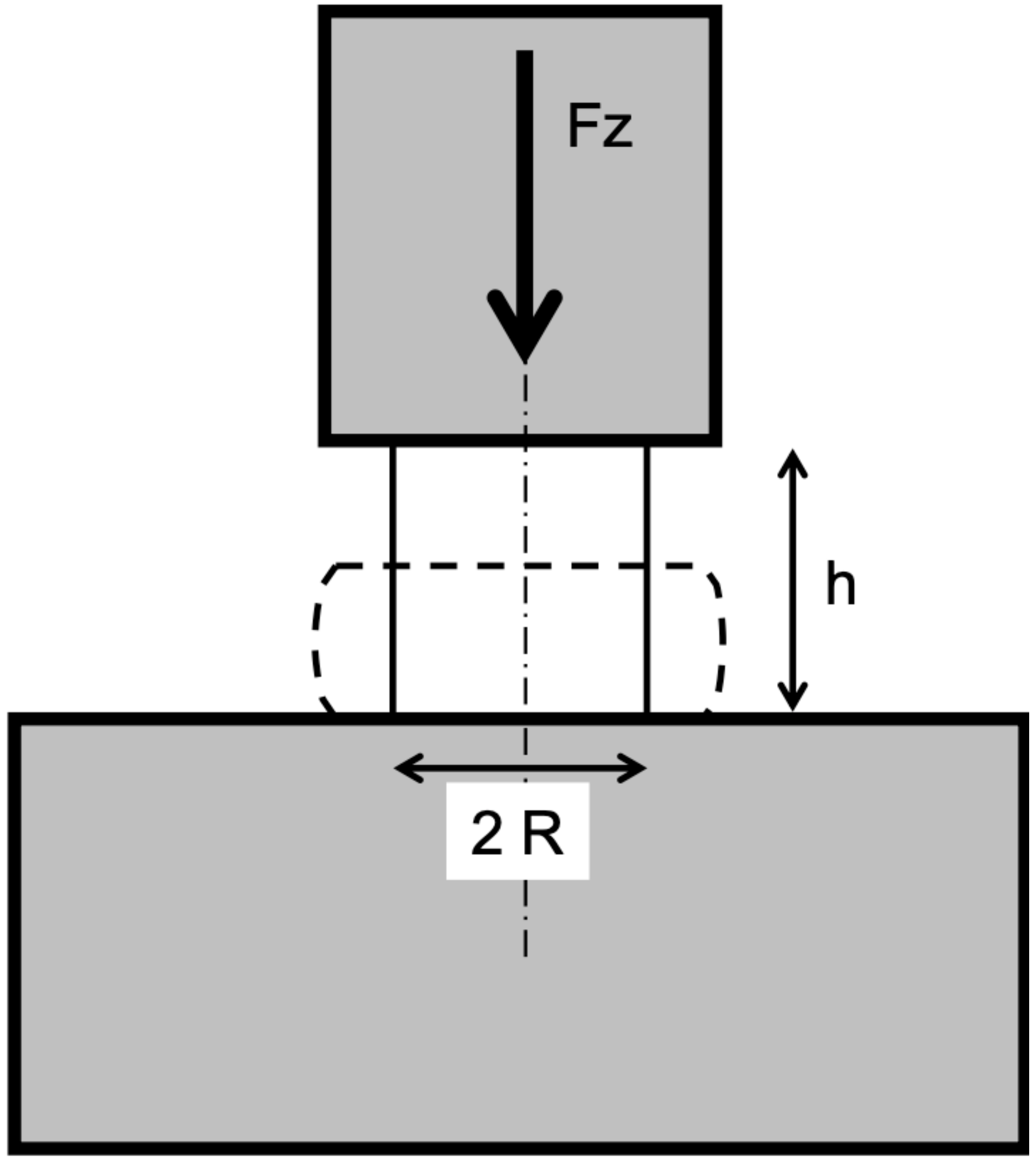
Stress/Strain → deformation force

- force dictates equipment and energy requirements

Friction → energy requirements, lubrication, quality (friction is not repeatable, coefficient is not constant)


BETA

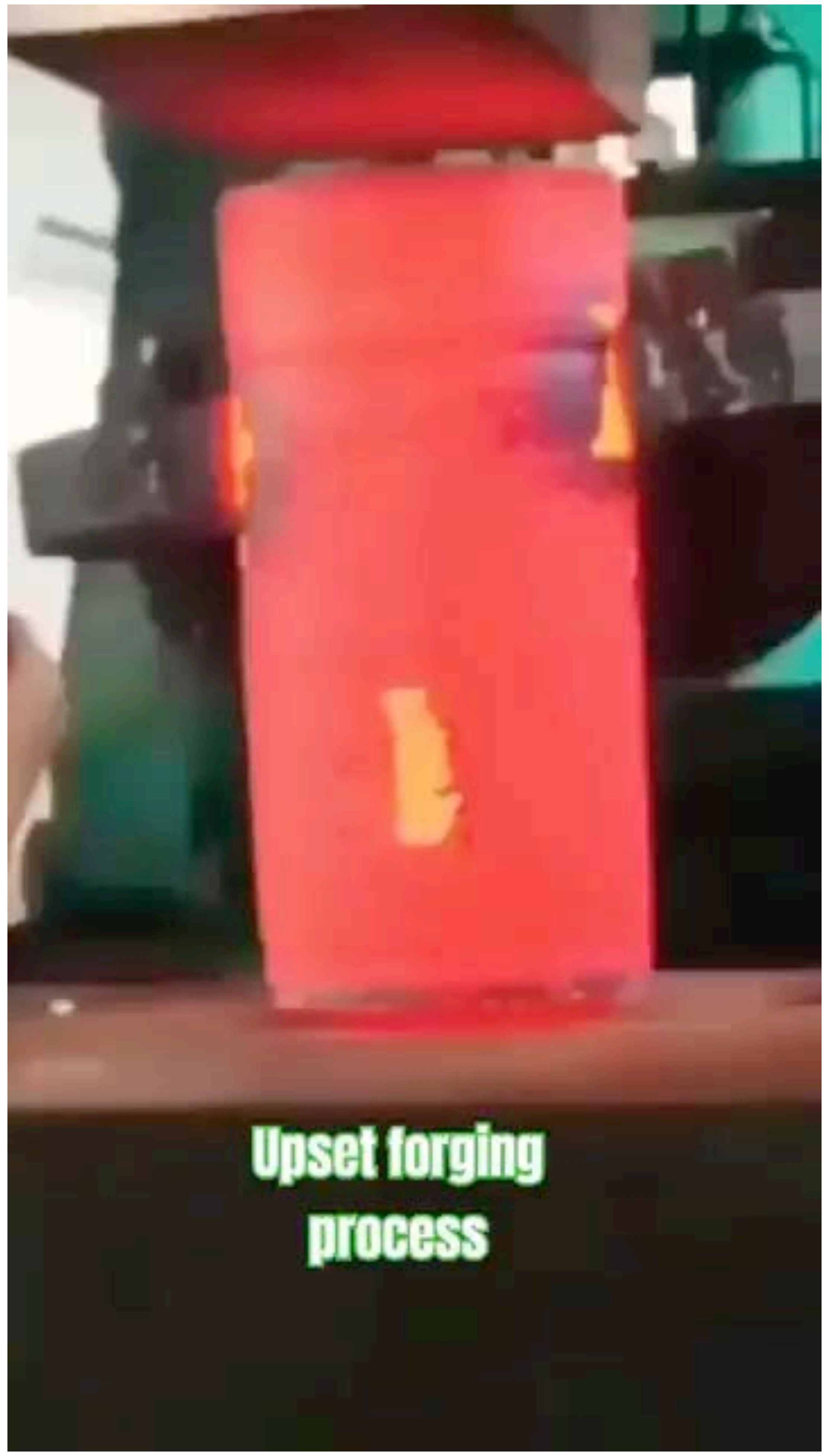
Forging Force and Friction



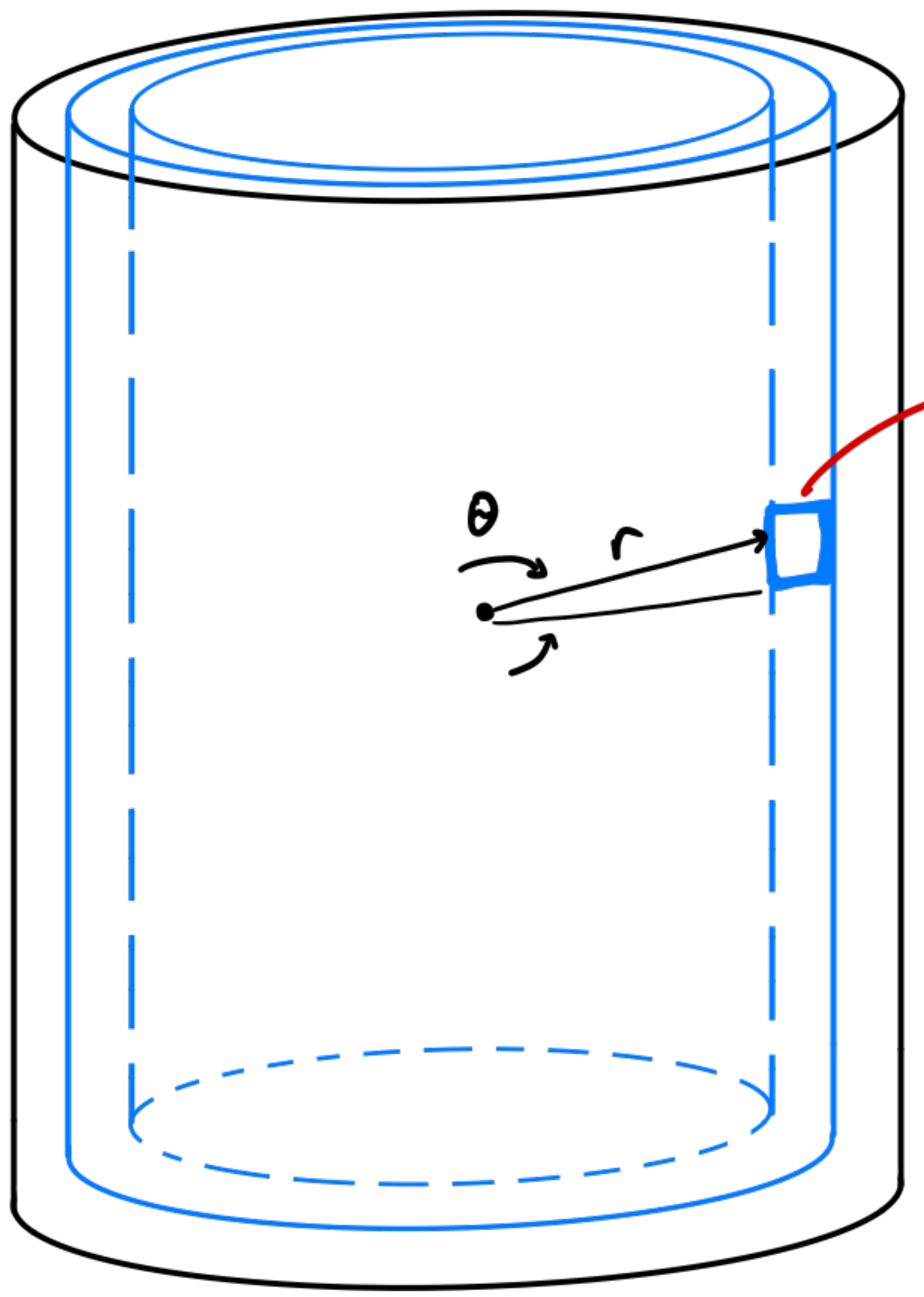
Axi-symmetric Upsetting

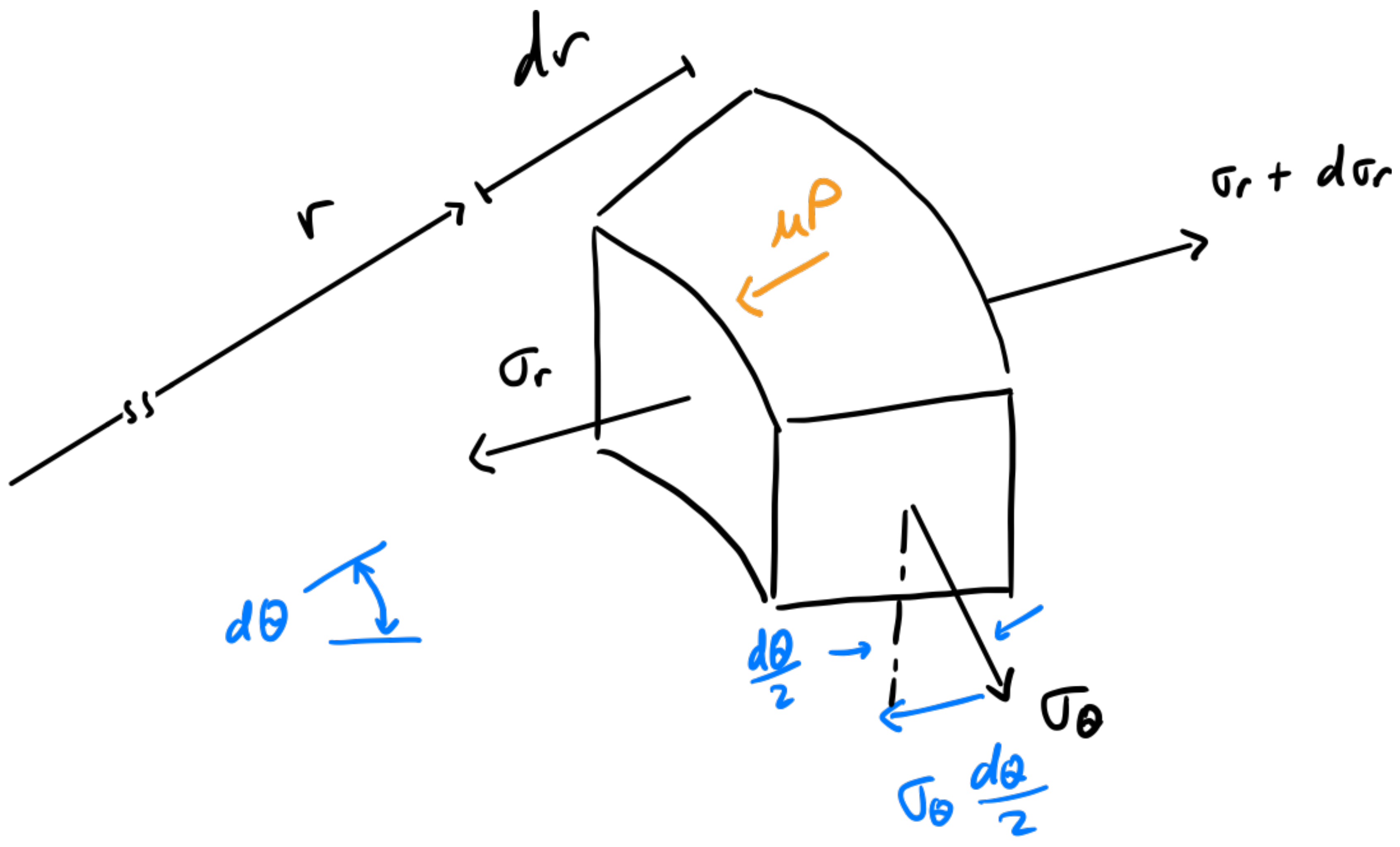
Assumptions:

- Tresca yield → plastic deformation → flow
- constant friction coefficient
- no “barreling”



Forging Force and Friction

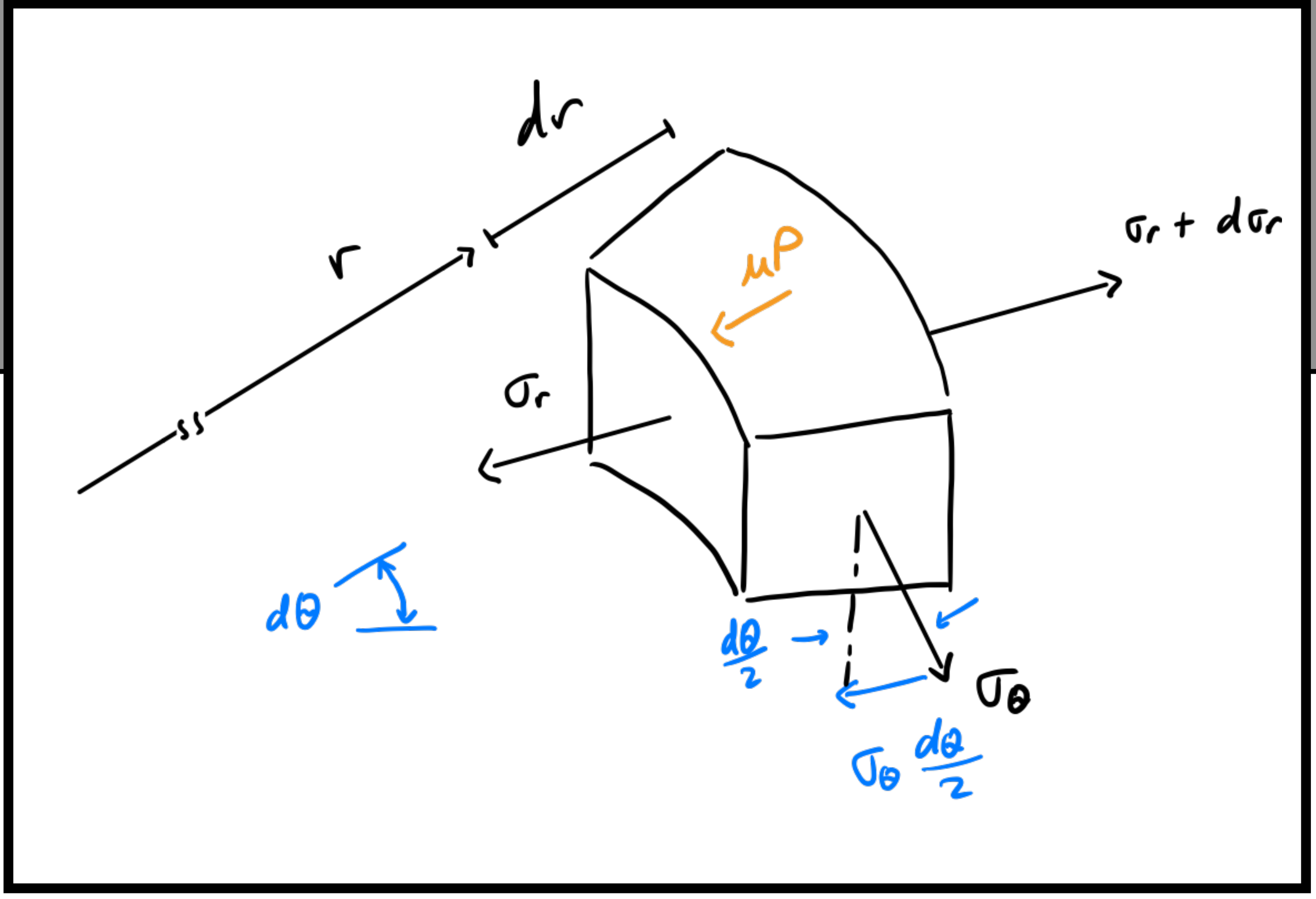




Eq. A: Equilibrium in the r direction

$$\sum dF_r = 0 = \underbrace{\sigma_r \cdot h \cdot r \cdot d\theta}_{\text{inner arc}} - \underbrace{2 \cdot \mu \cdot P \cdot r \cdot d\theta \cdot dr}_{\text{friction top and bottom}} - \underbrace{2 \cdot \sigma_\theta \cdot h \cdot dr}_{\text{hoop}} \cdot \frac{d\theta}{2} + \underbrace{(\sigma_r + d\sigma_r) \cdot (r + dr) \cdot h \cdot d\theta}_{\text{outer arc}}$$

$$\frac{d\sigma_r}{r} = \frac{2\mu P}{h} = -\frac{2\mu\sigma_z}{h}$$



Forging Force and Friction

Eq. A: Equilibrium in the r direction

$$\sum dF_r = 0 = \underbrace{\sigma_r \cdot h \cdot r \cdot d\theta}_{\text{inner arc}} - \underbrace{2 \cdot \mu \cdot P \cdot r \cdot d\theta \cdot dr}_{\text{friction top and bottom}} - \underbrace{2 \cdot \sigma_\theta \cdot h \cdot dr \cdot}_{\text{hoop}} \frac{d\theta}{2} + \underbrace{(\sigma_r + d\sigma_r) \cdot (r + dr) \cdot h \cdot d\theta}_{\text{outer arc}}$$

$$\frac{d\sigma_r}{r} = \frac{2\mu P}{h} = -\frac{2\mu\sigma_z}{h}$$

Eq. B: Tresca Yield Criterion

$$\sigma_r - \sigma_z = Y \quad \rightarrow \quad \frac{d\sigma_z}{dr} = \frac{d\sigma_r}{dr}$$

$$\boxed{\sigma_z = -Y \cdot e^{\frac{2\mu}{h}(R-r)}}$$

Forging Force and Friction

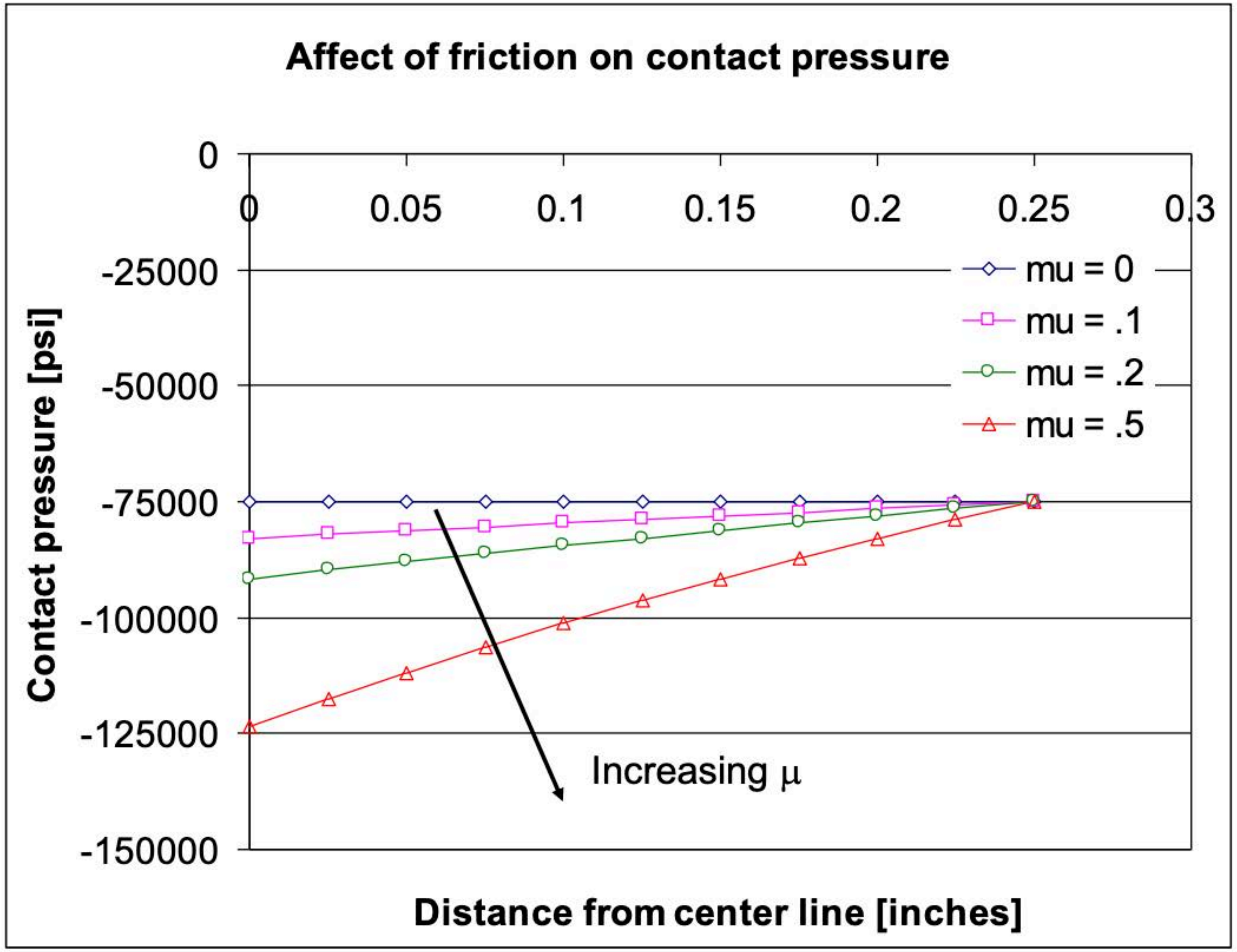
$$F_z = \int_0^R \sigma_z \cdot 2 \cdot \pi \cdot r \cdot dr = (\pi \cdot R^2) \cdot \frac{1}{2} \cdot \left(\frac{h}{\mu R}\right)^2 \cdot Y \cdot \left(e^{\frac{2\mu R}{h}} - \frac{2\mu R}{h} - 1\right)$$

Use Taylor's series expansion to approximate the exponential and expand about 0 (valid for small 2μR/h)

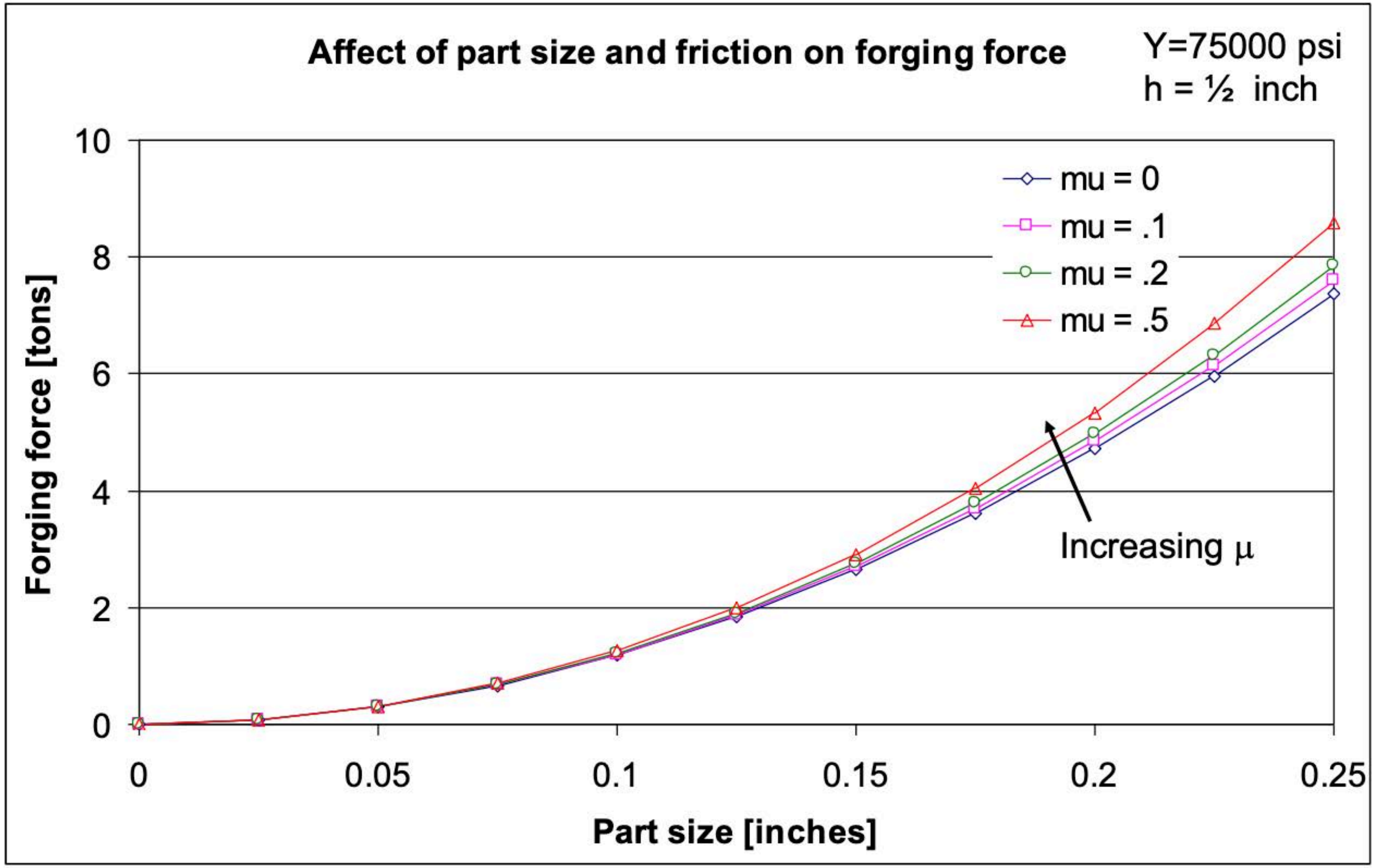
$$\boxed{|F_z| = (\pi R^2) \cdot Y \cdot \left(1 + \frac{2\mu R}{3h}\right)}$$

Forging Force and Friction

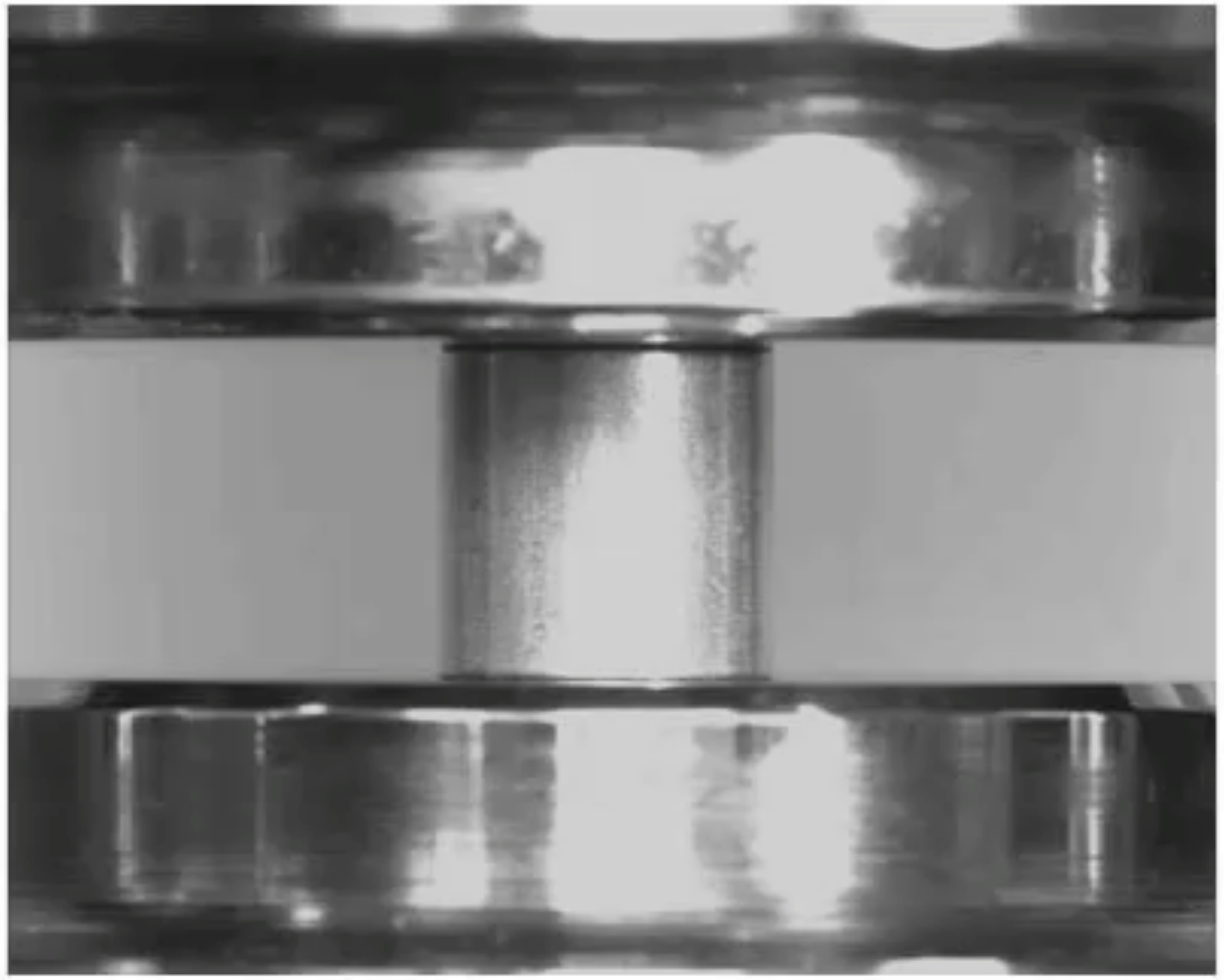
Y=75000 psi
h = ½ inch

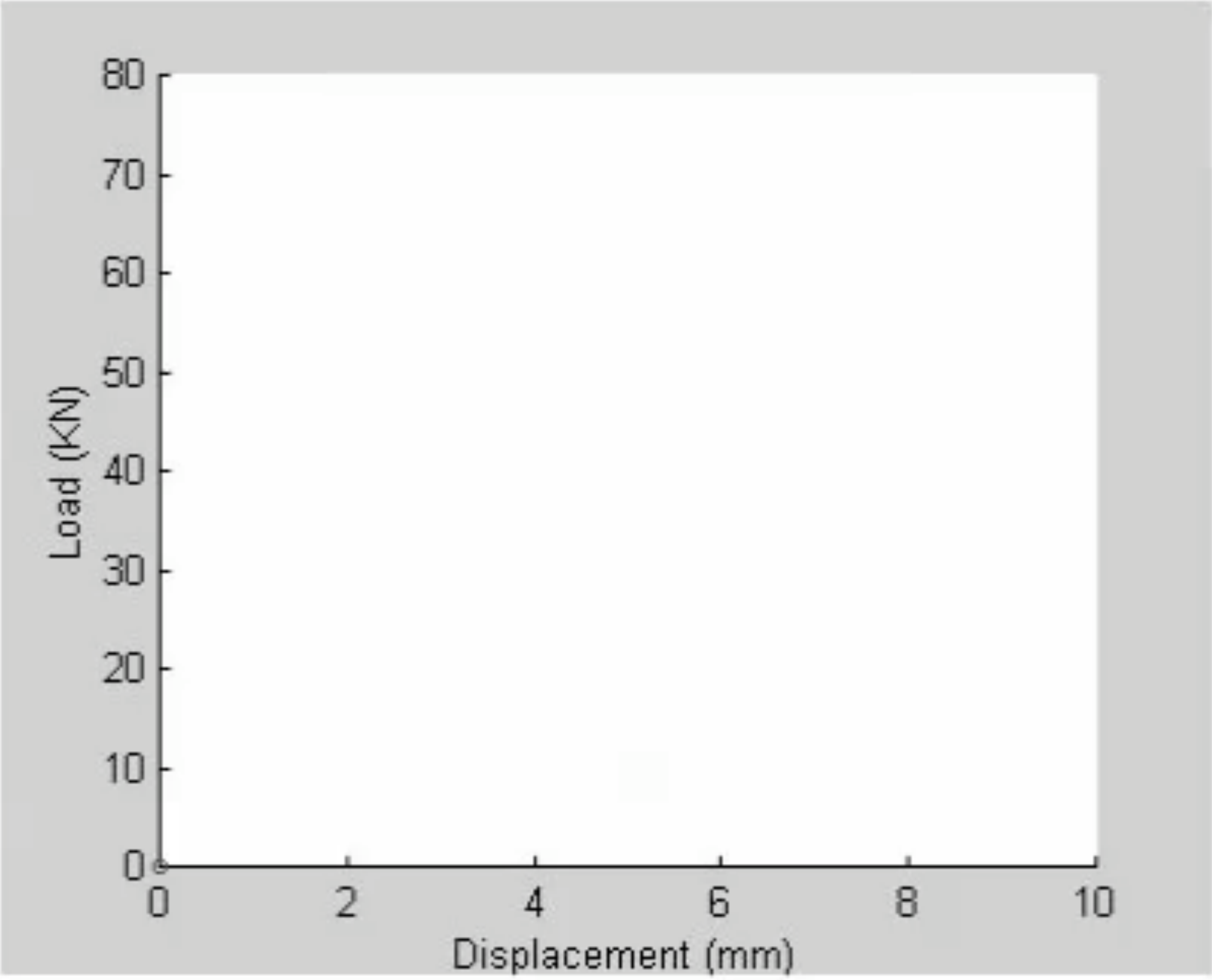


Forging Force and Friction

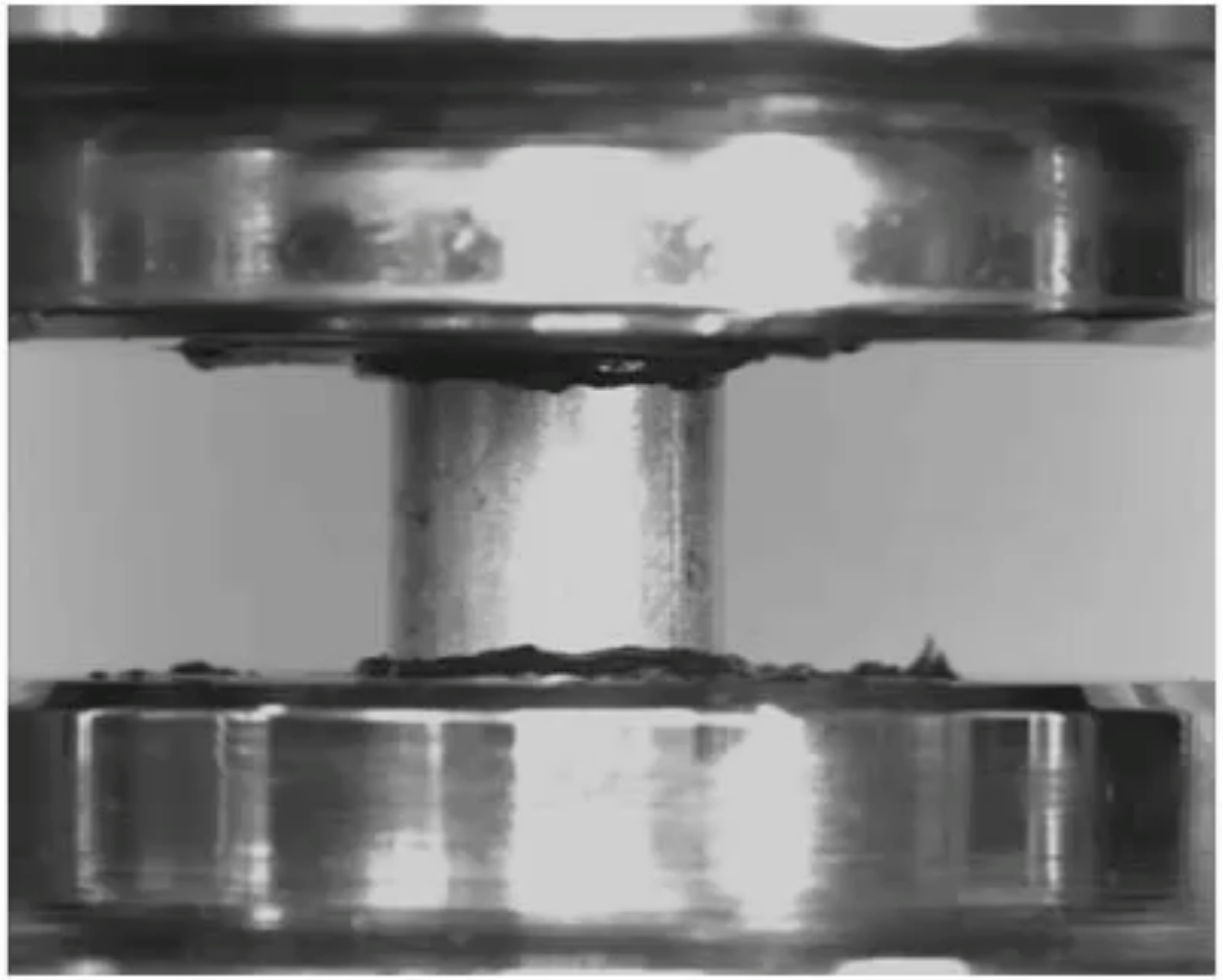


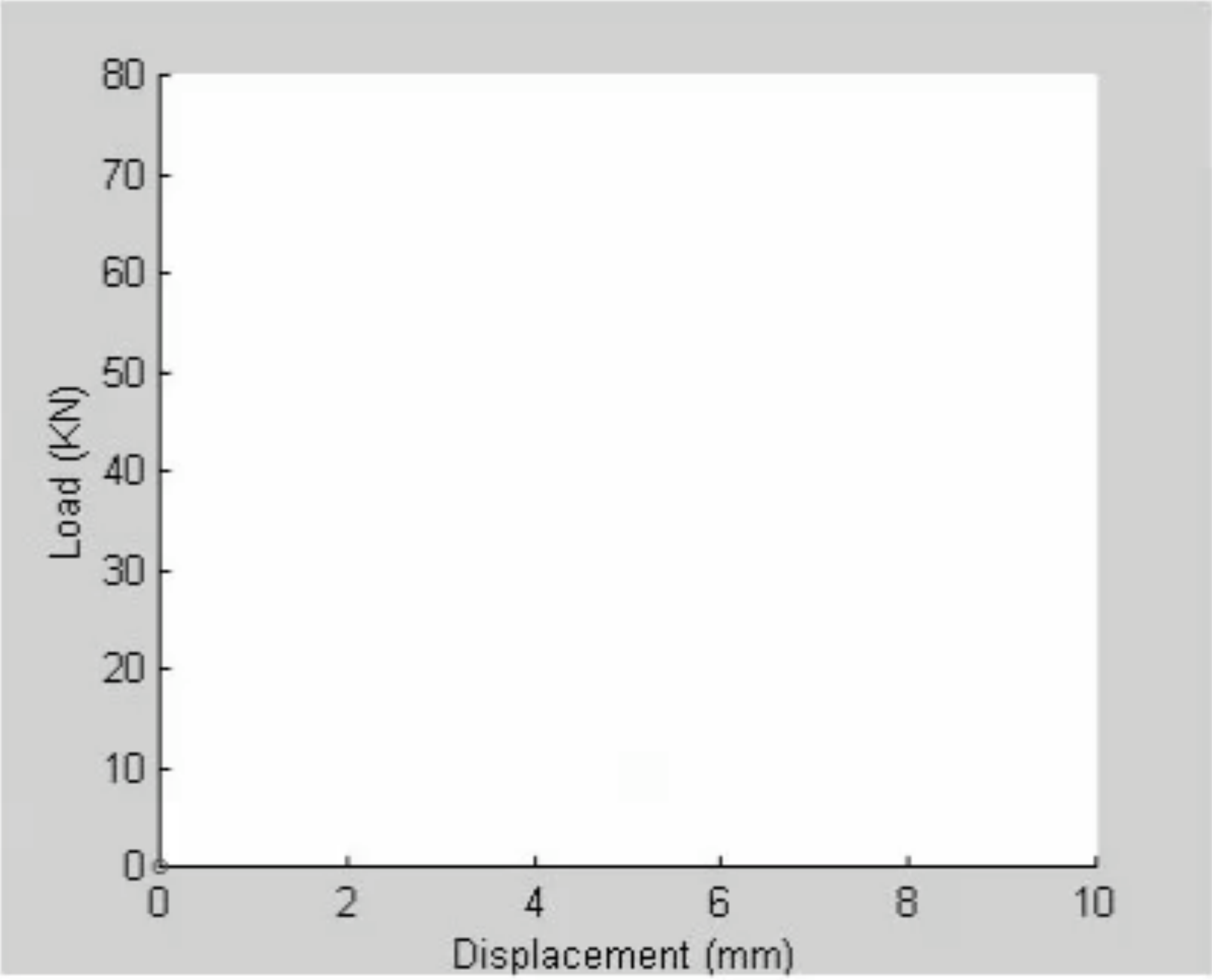
Upsetting with Friction





Upsetting without Friction



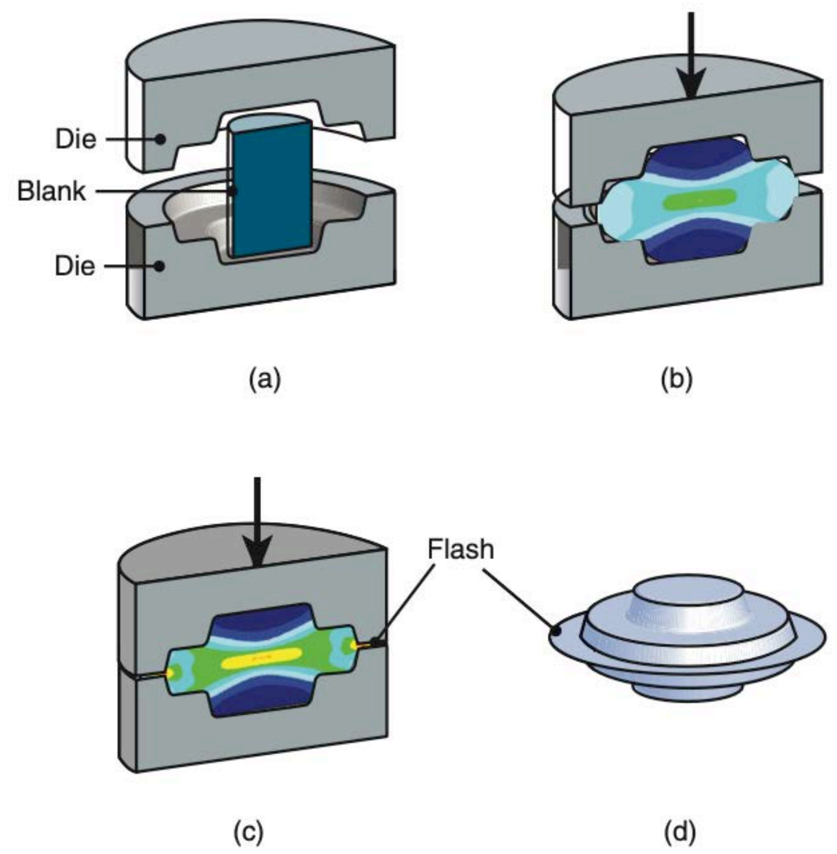


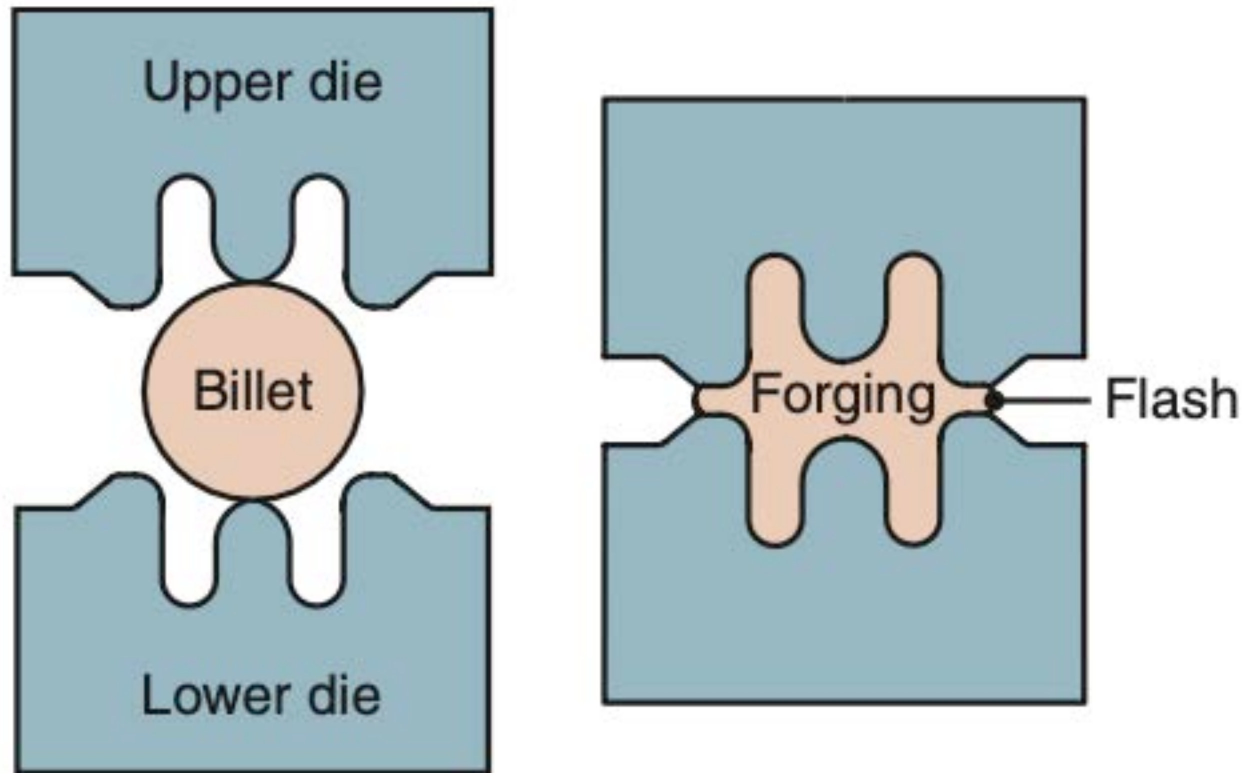
Deforming

Forging, Extrusion, Sheet Metal: Processes and Equipment

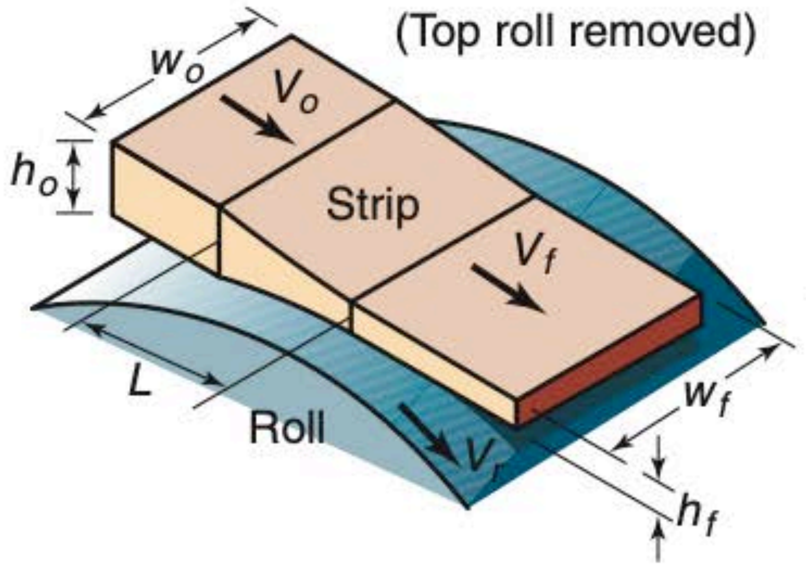
Common Bulk Processes

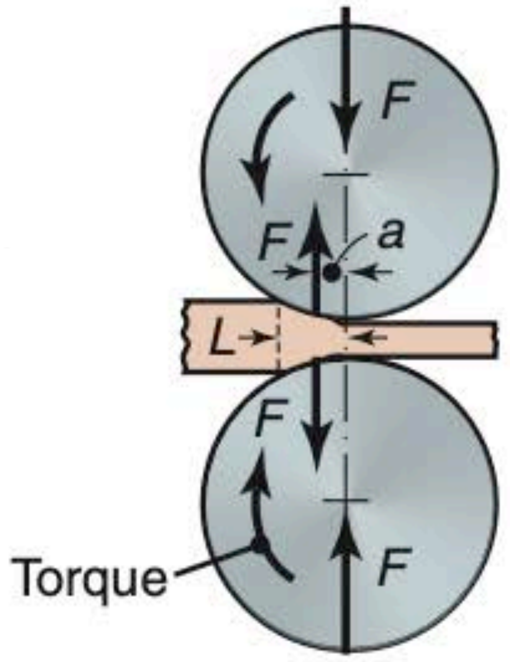
Forging

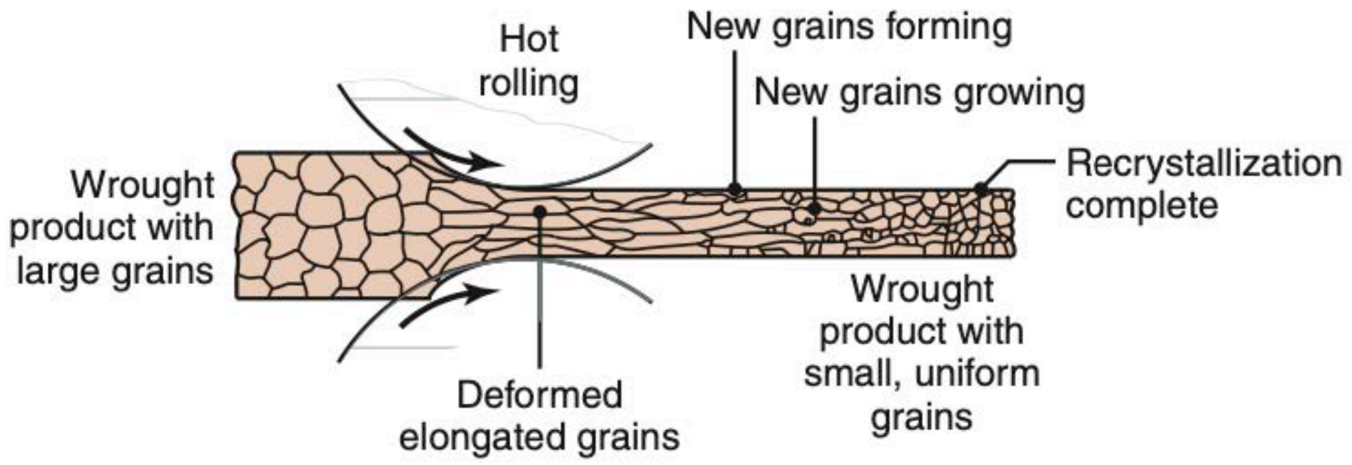


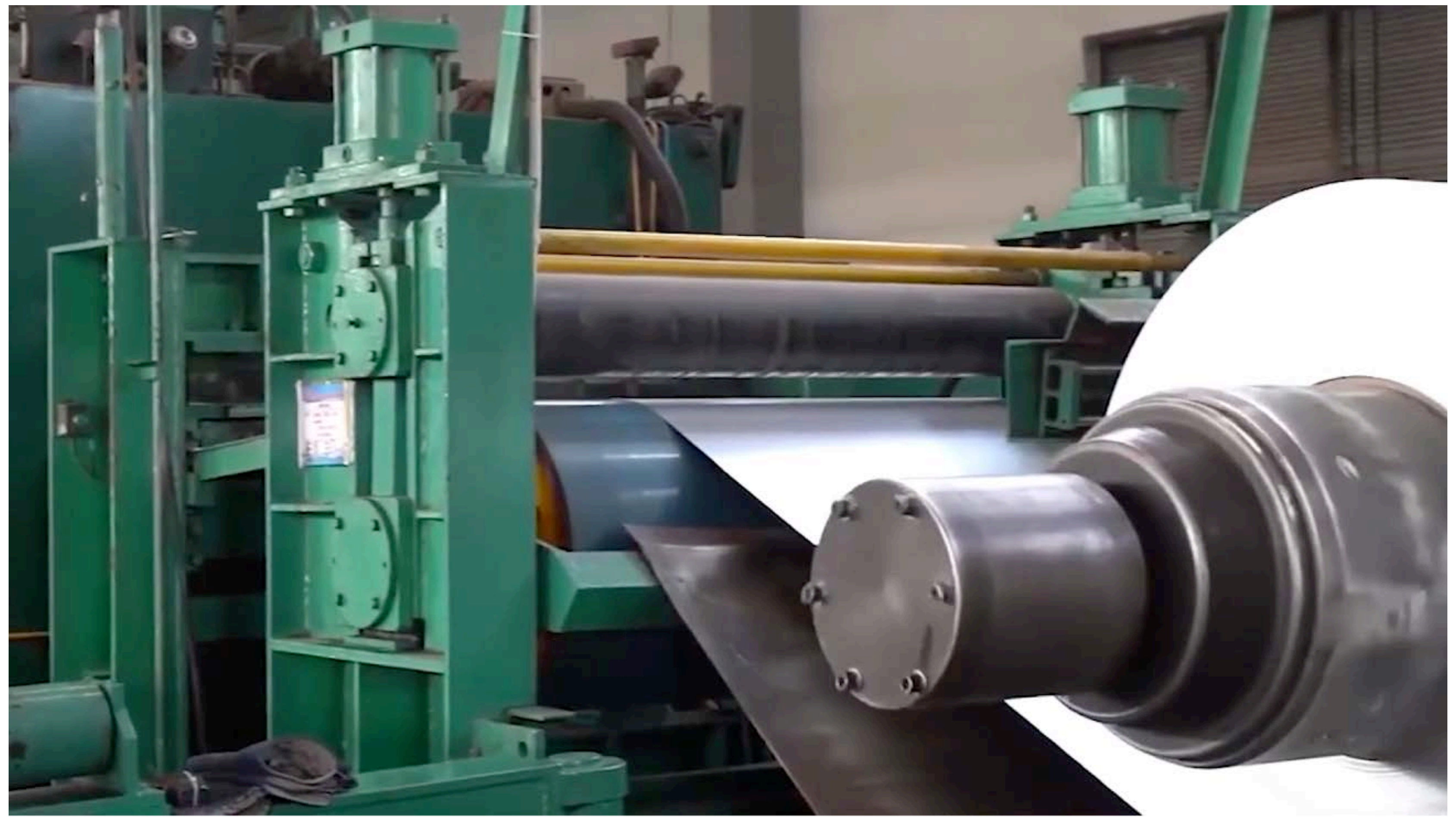


Rolling

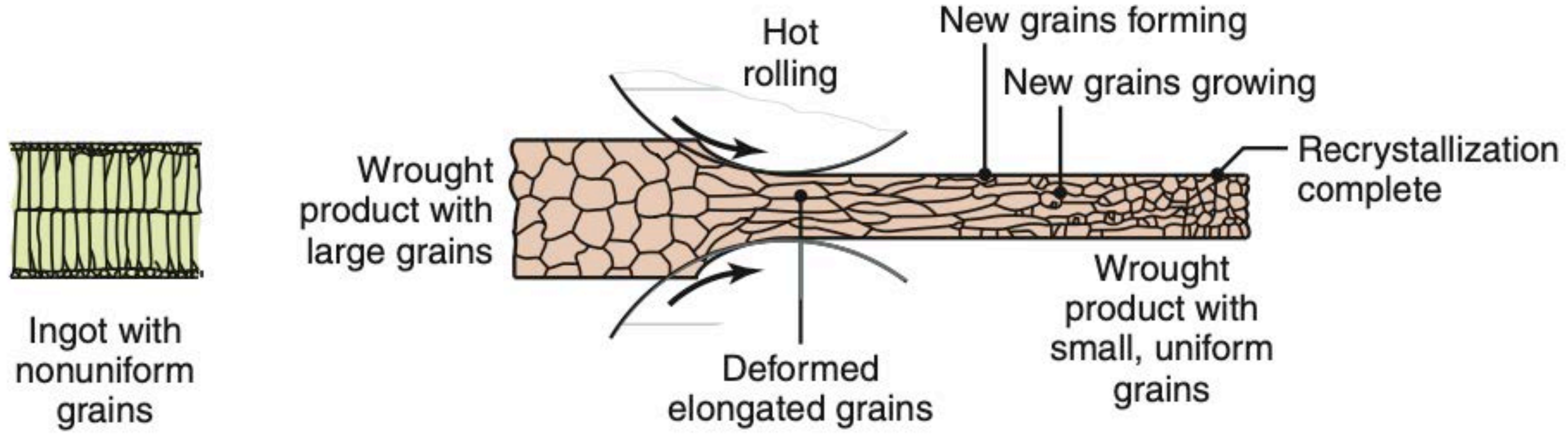








Microstructure: Grain Size



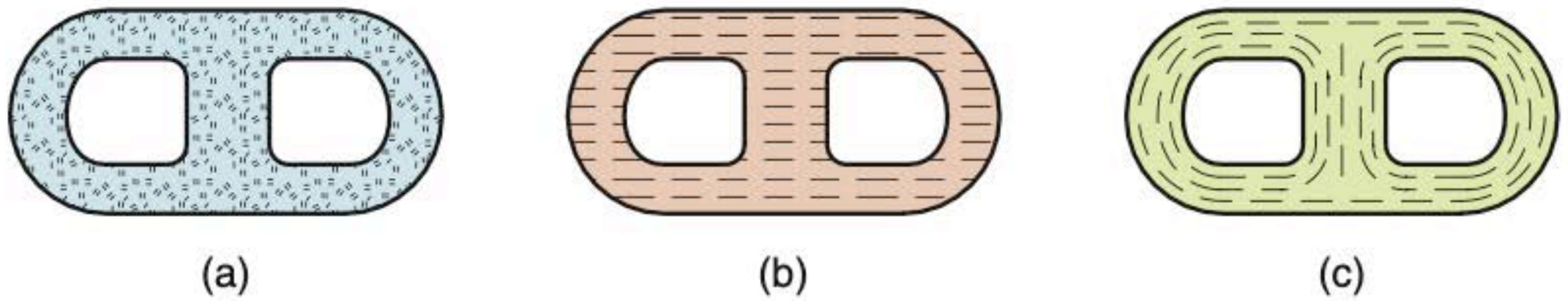


Figure 14.2: Schematic illustration of a part (dragline chain link, approximately 2-m long) made by three different processes and showing grain flow. (a) Casting by the processes described in Chapter 11. (b) Machining from a blank, described in Part IV of this book, and (c) forging. Each process has its own advantages and limitations regarding external and internal characteristics, material properties, dimensional accuracy, surface finish, and the economics of production. *Source:* Courtesy of the Forging Industry Association.

material properties affected by grain size:

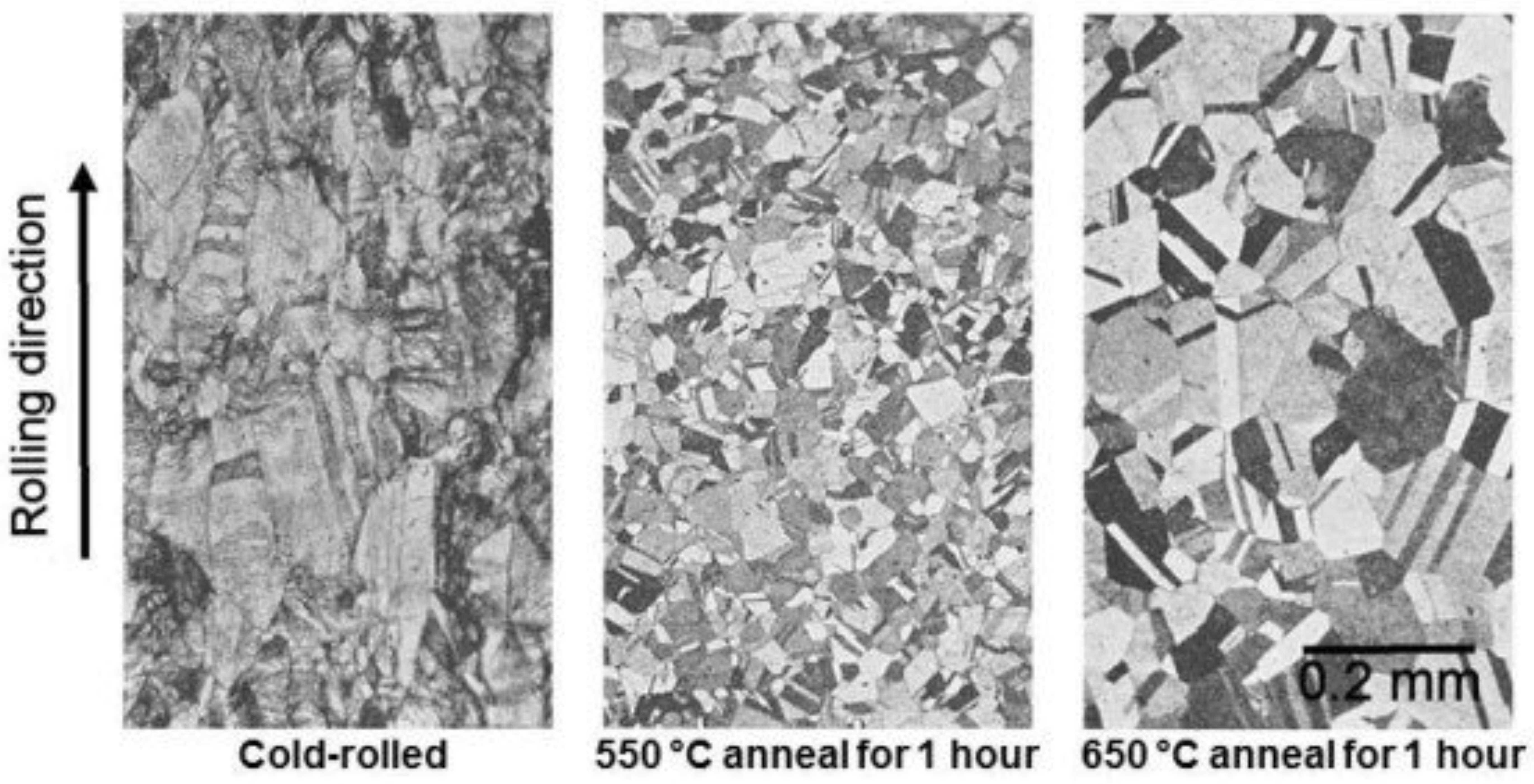
- strength
- hardness
- ductility

Hall-Petch model: smaller grains give higher strength

$\boldsymbol{\sigma}_0$ = stress to start dislocation movement
$\boldsymbol{k_y}$ = material hardening constant
$\boldsymbol{d}$ = grain size

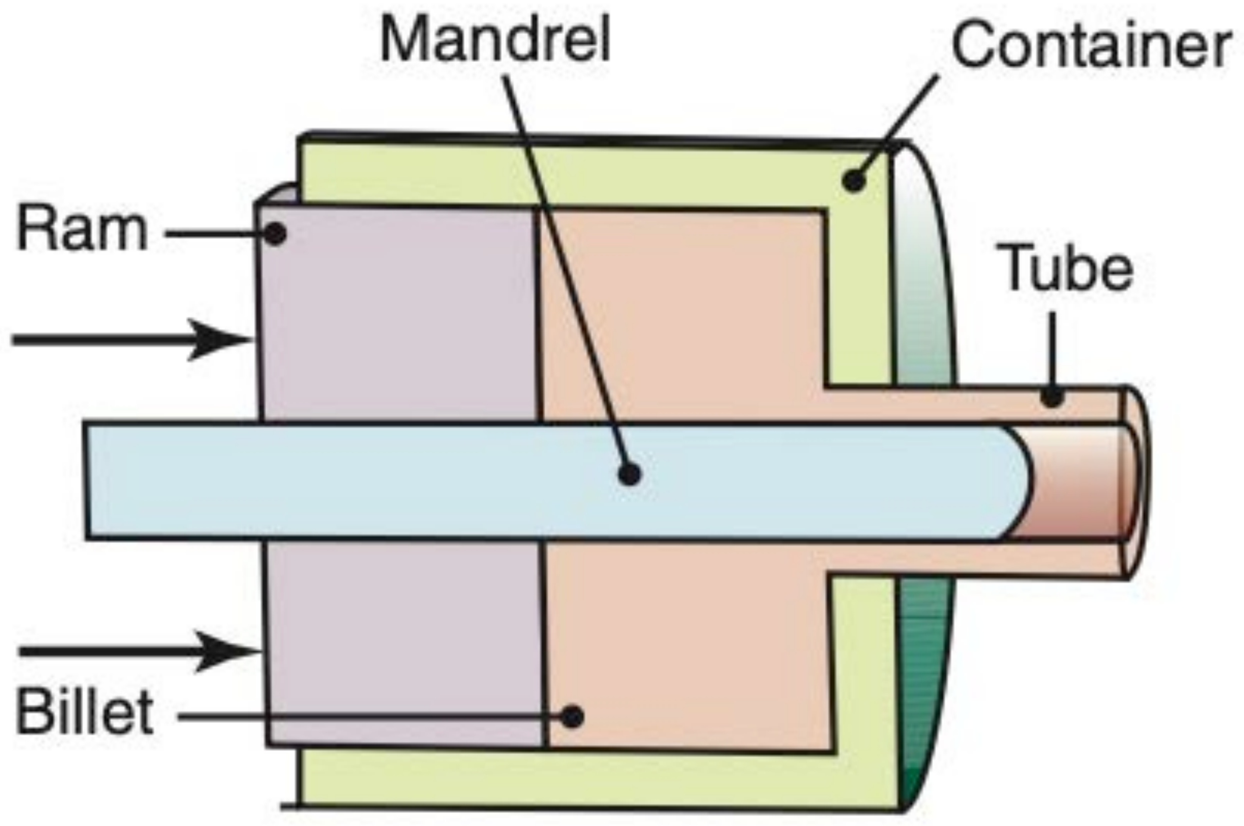
$$\sigma_y = \sigma_o + \frac{k_y}{\sqrt{d_{grain}}}$$

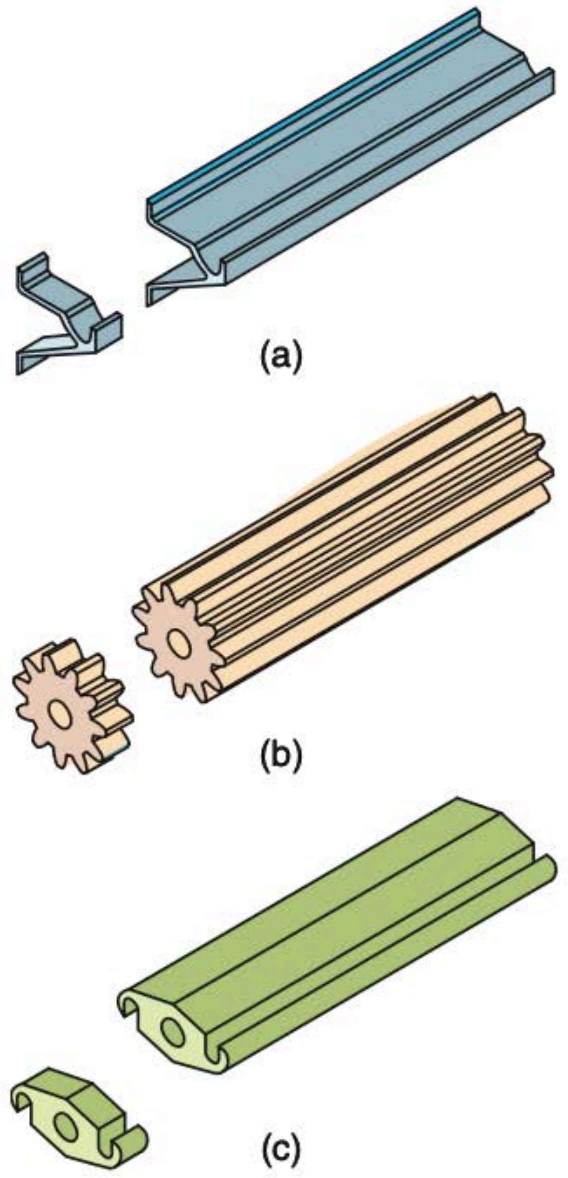
Recrystallization

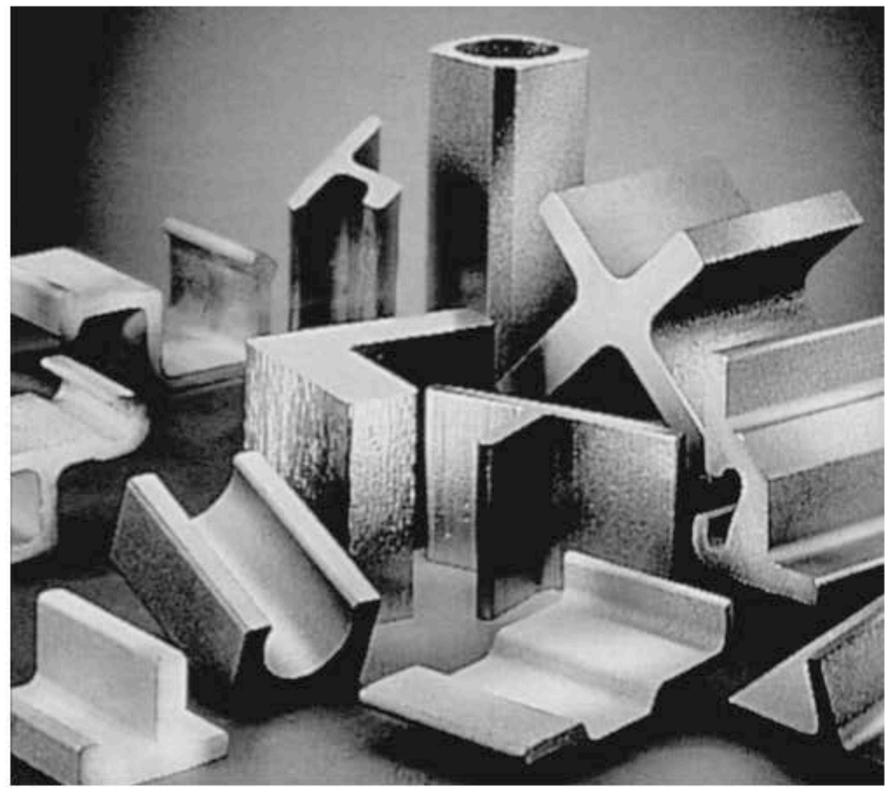


Common Processes

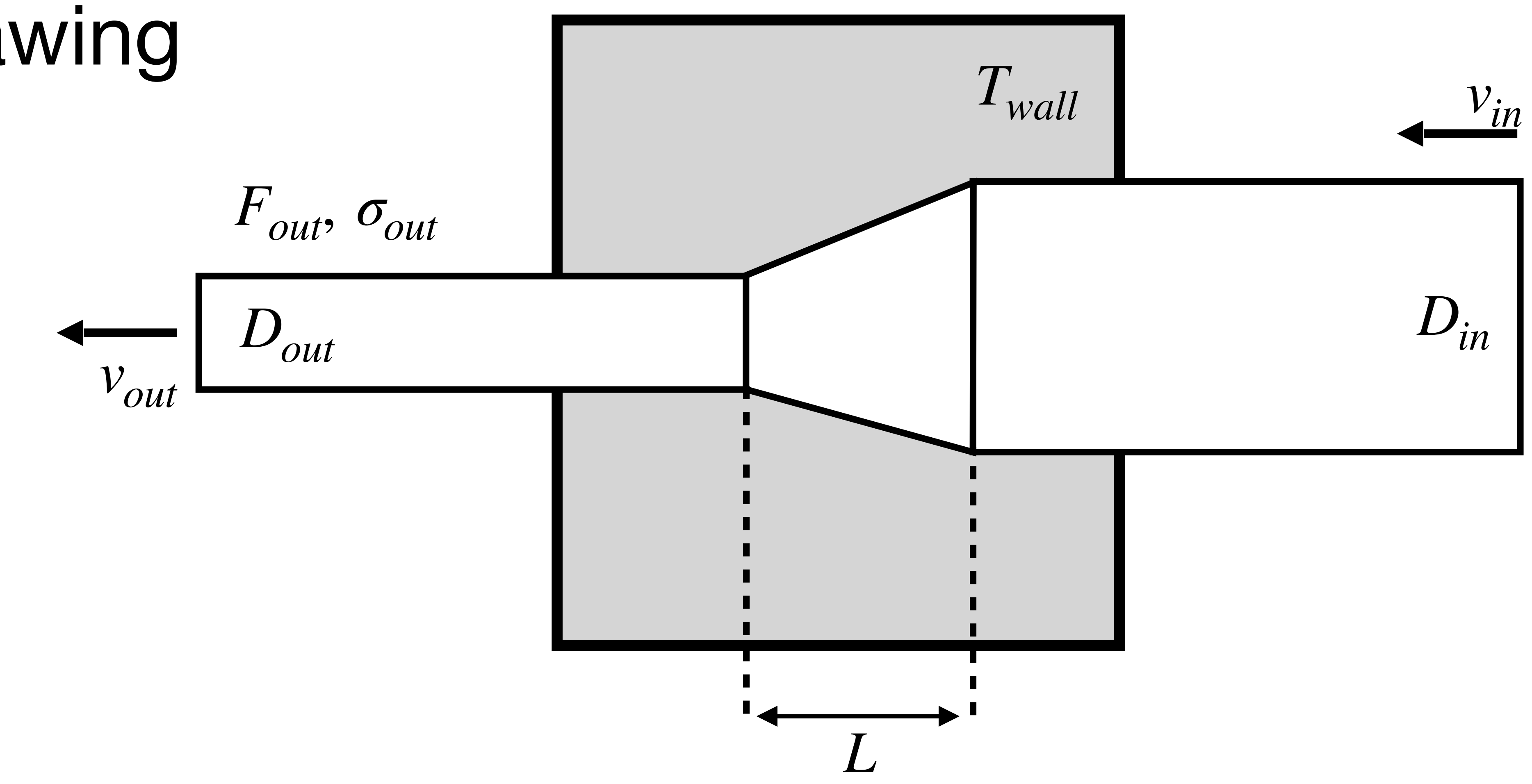
Extrusion

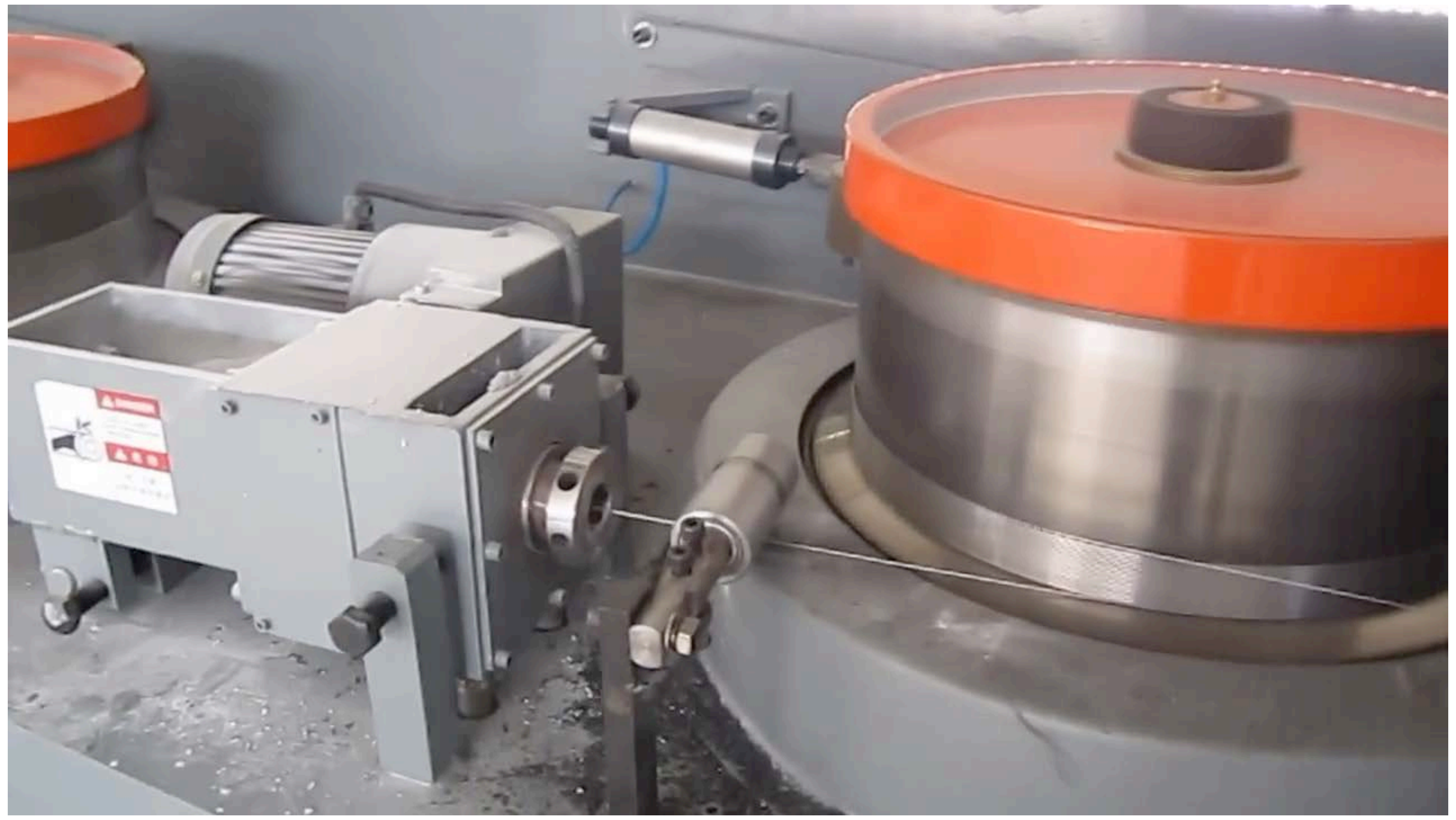






Drawing





Extrusion Demo

	Trial #1	Trial #2	Trial #3
Initial Shape	2.625”	2.625”	2.625”
Final Shape	0.700”	0.500”	1” × 1”
Final Area	0.4 in^2	0.2 in^2	~0.2 in^2

Deforming

Forging, Extrusion, Sheet Metal: Processes and Equipment

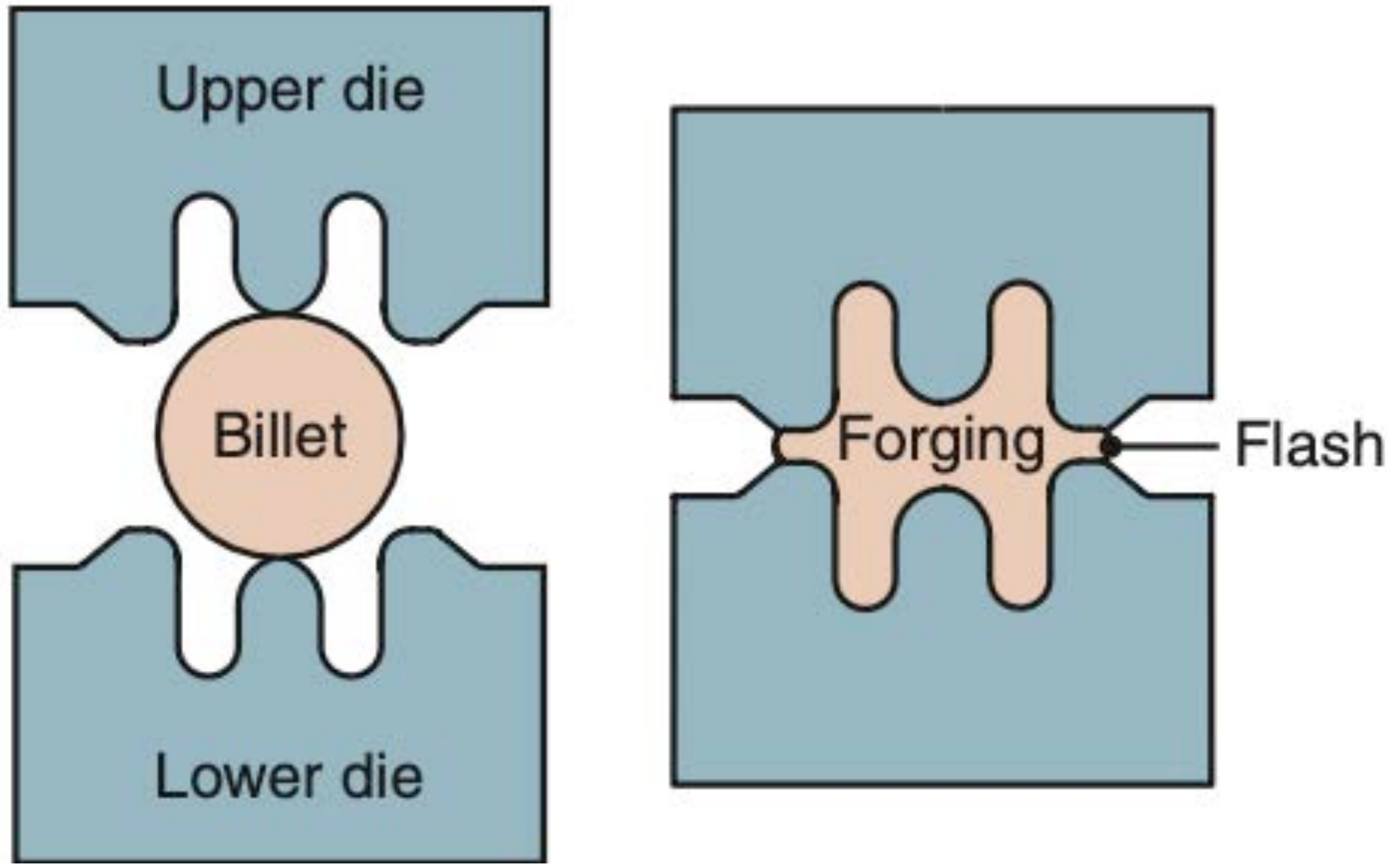
DFM for Deforming

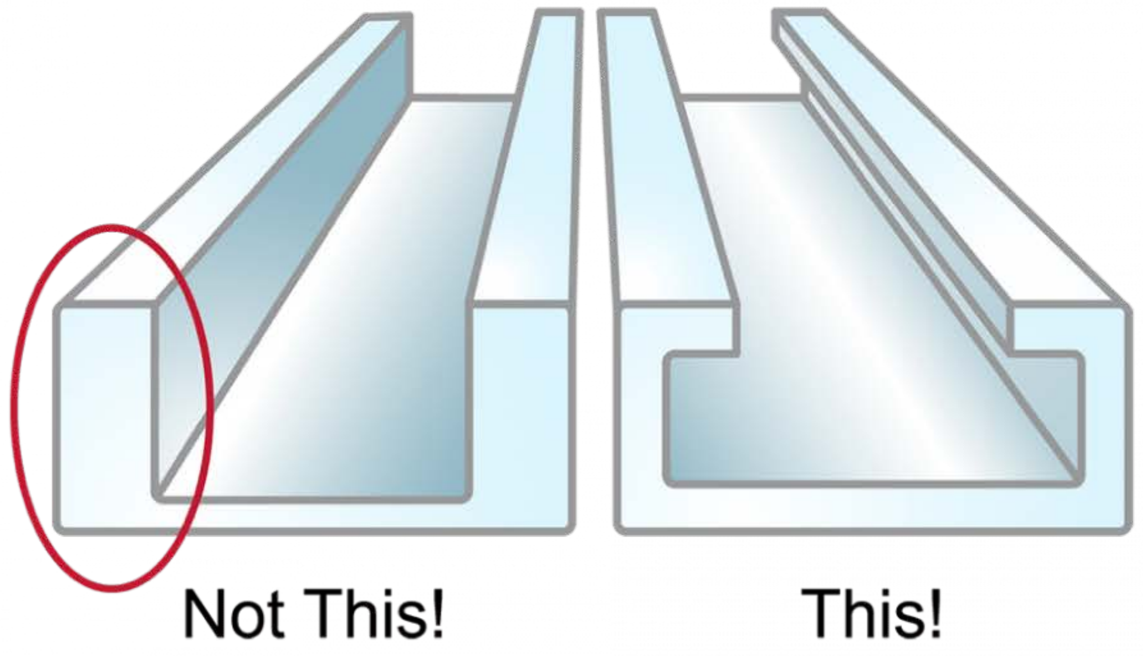
parting line + flash handling

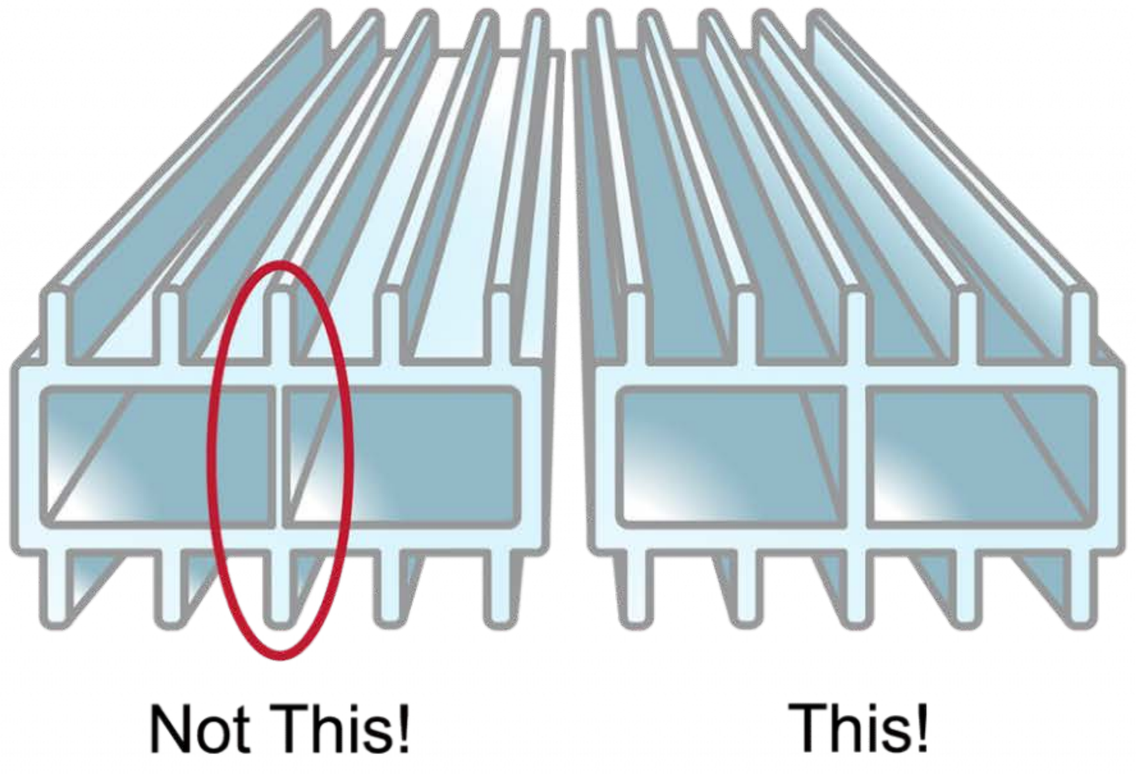
draft angles to eject part

avoid sharp corners to fill appropriately

lubrication







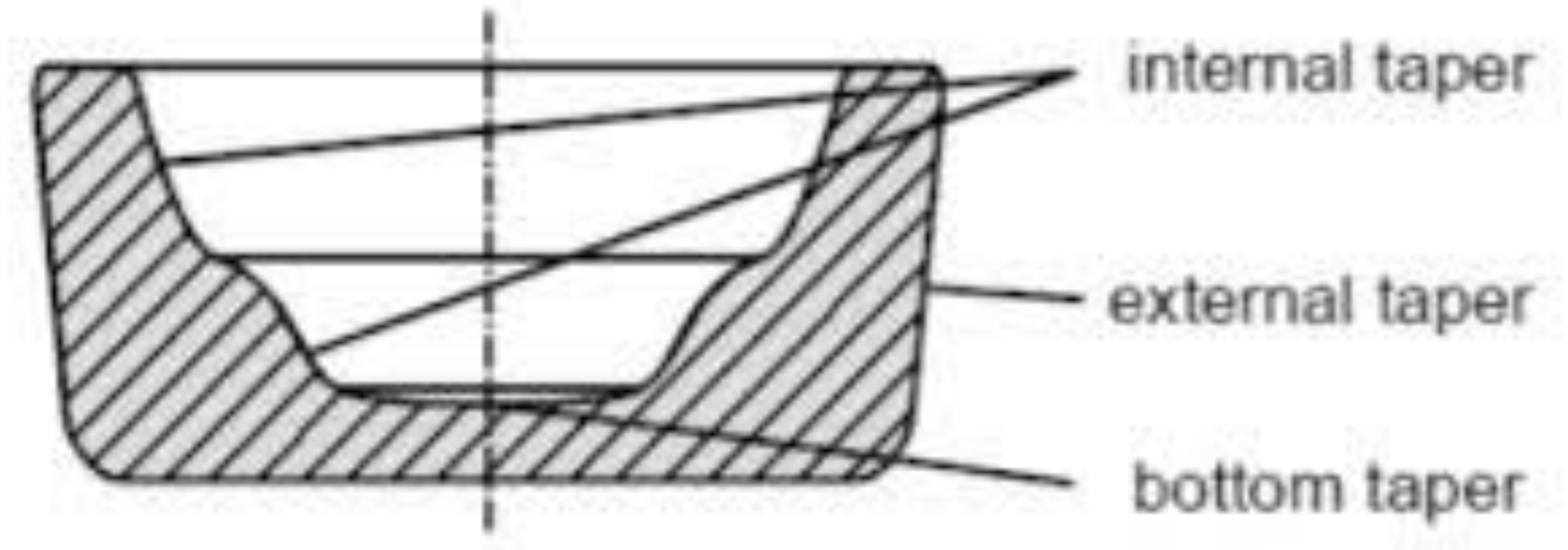
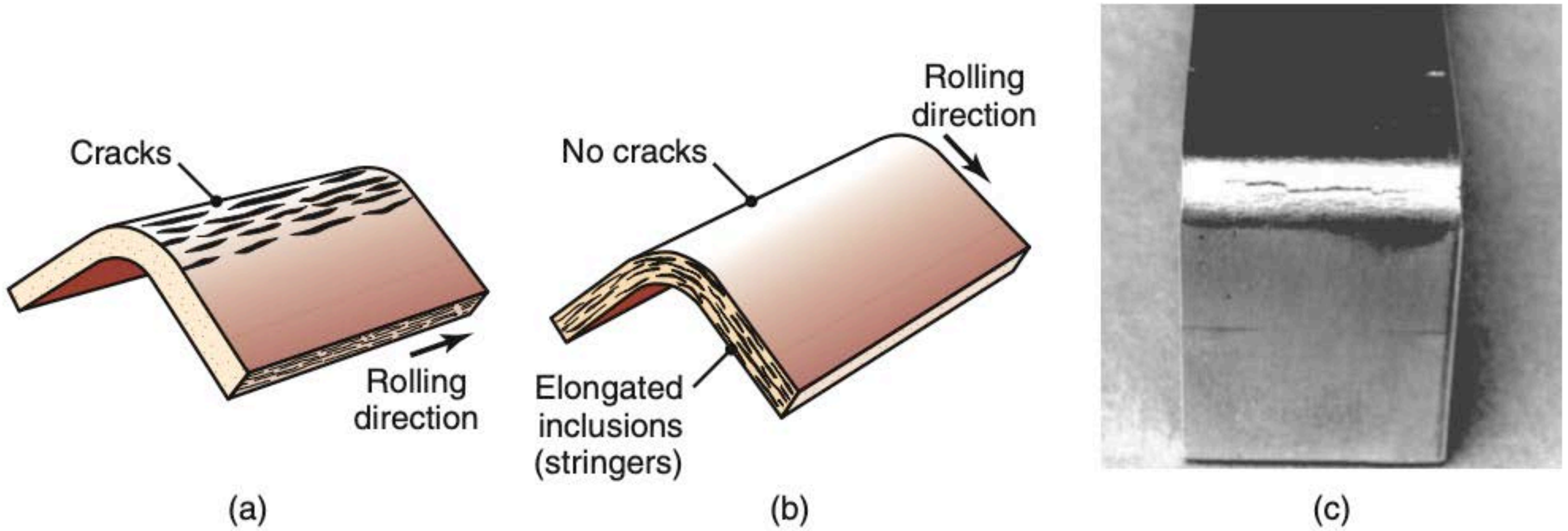
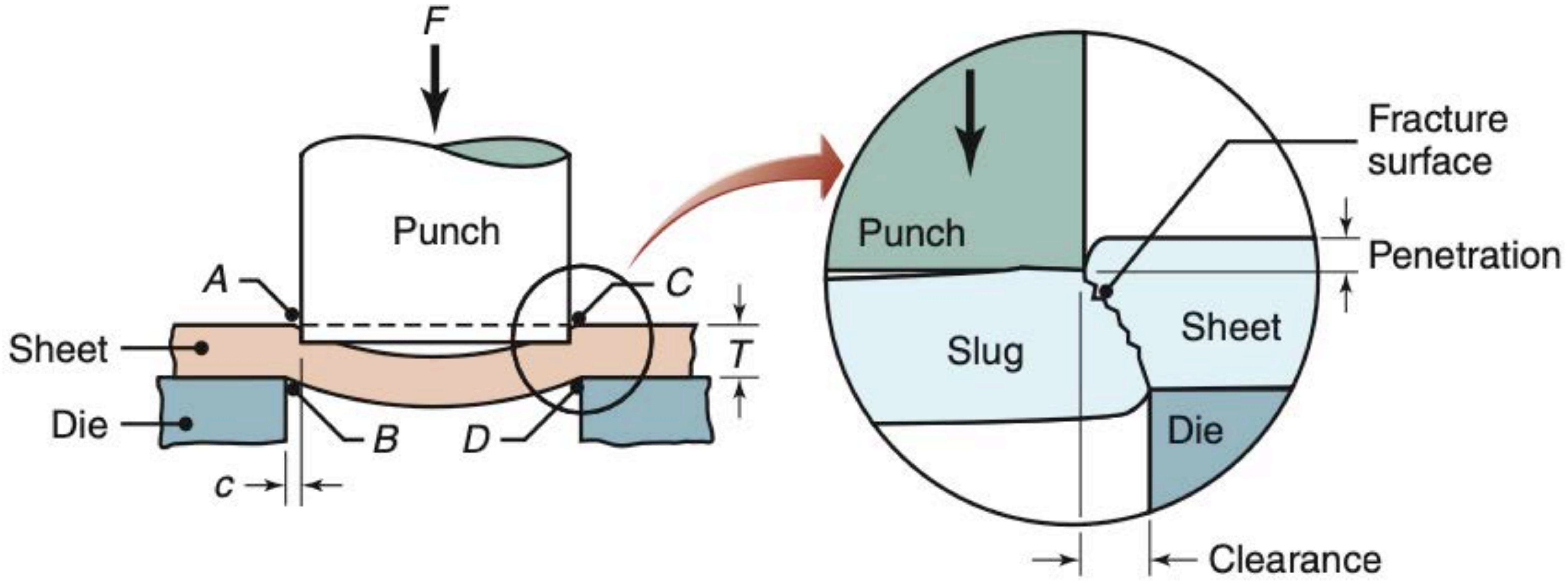


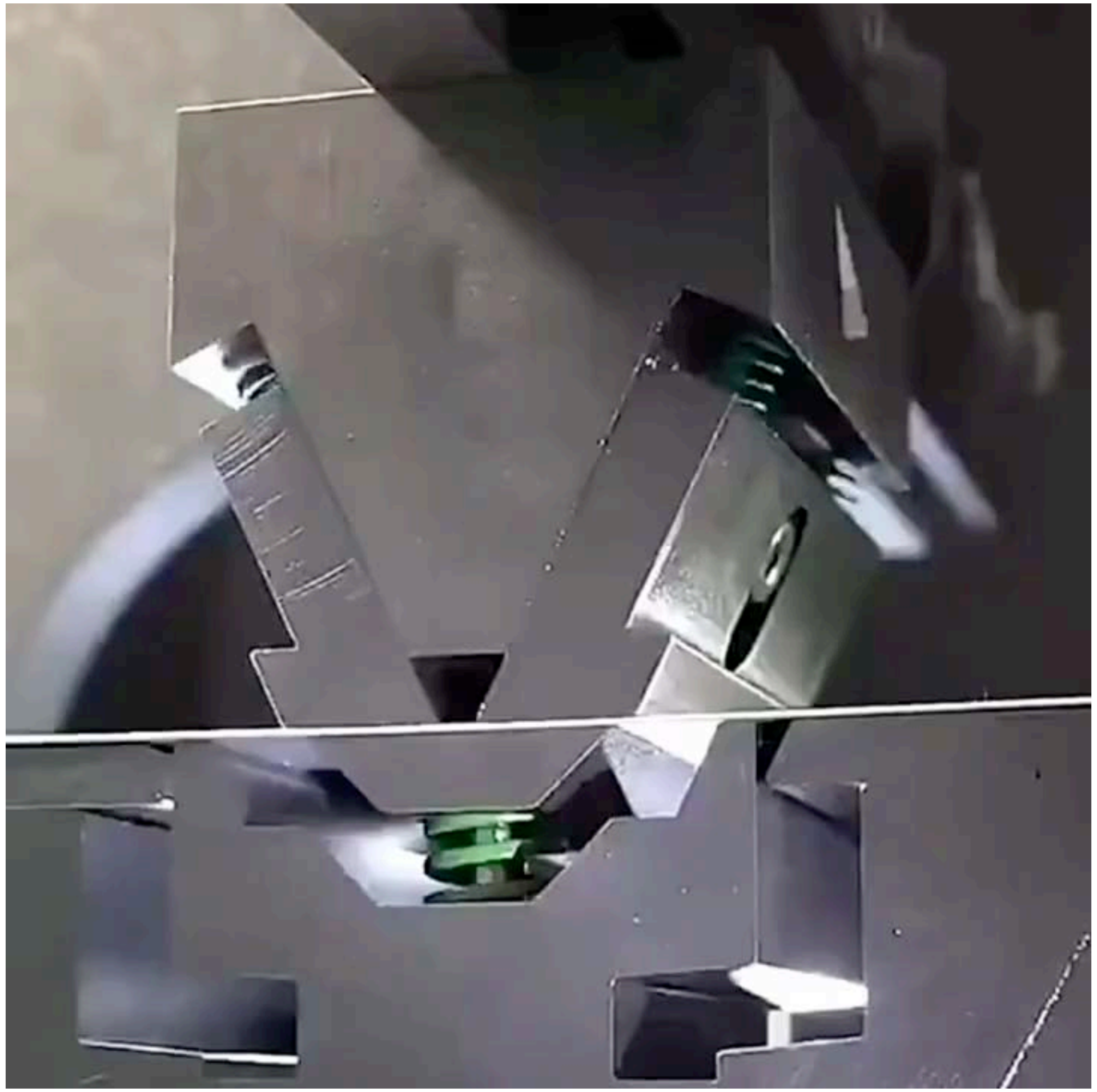
Illustration of Draft

Common Sheet Forming Processes

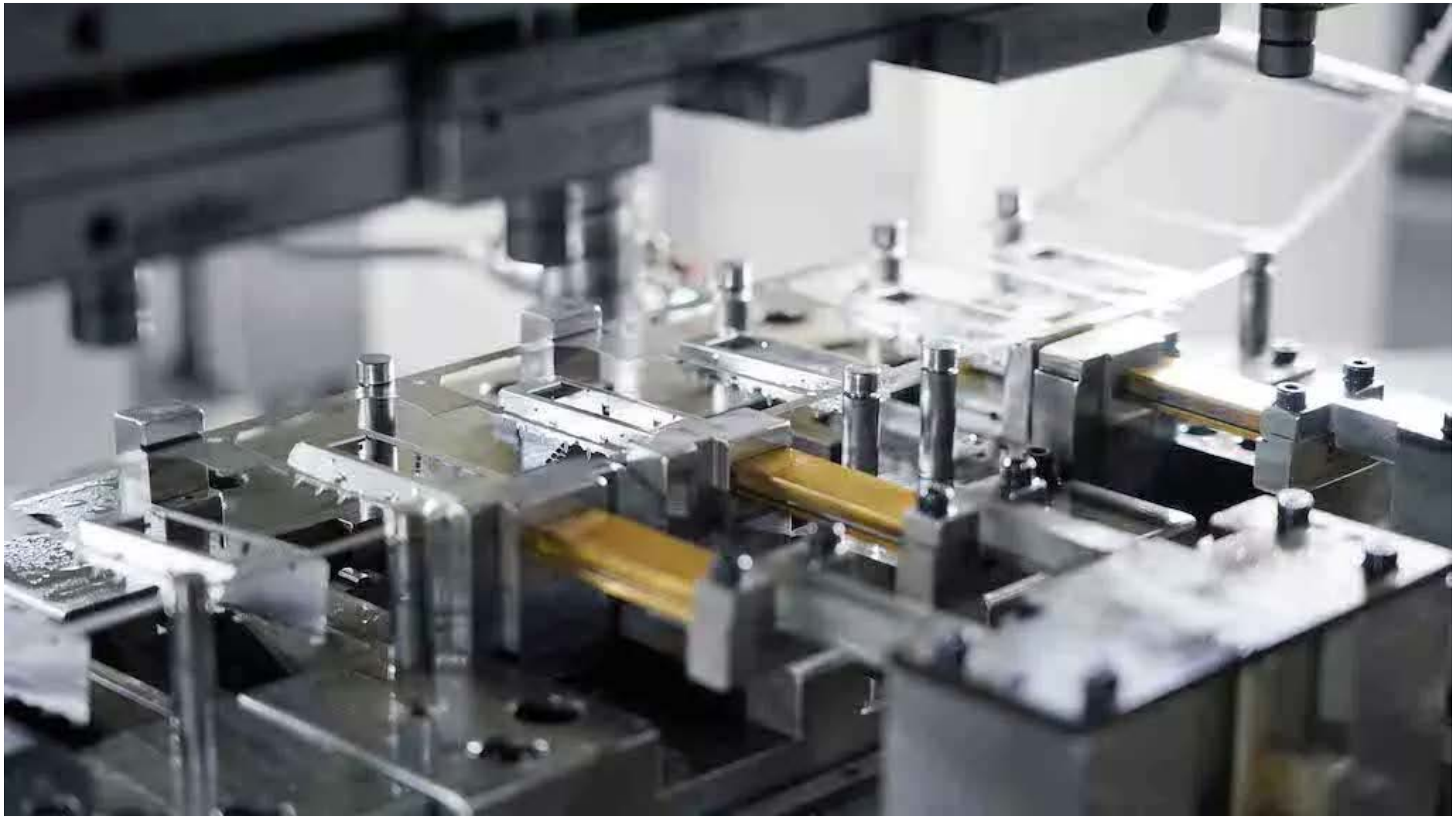
Sheet Metal Bending/Stamping







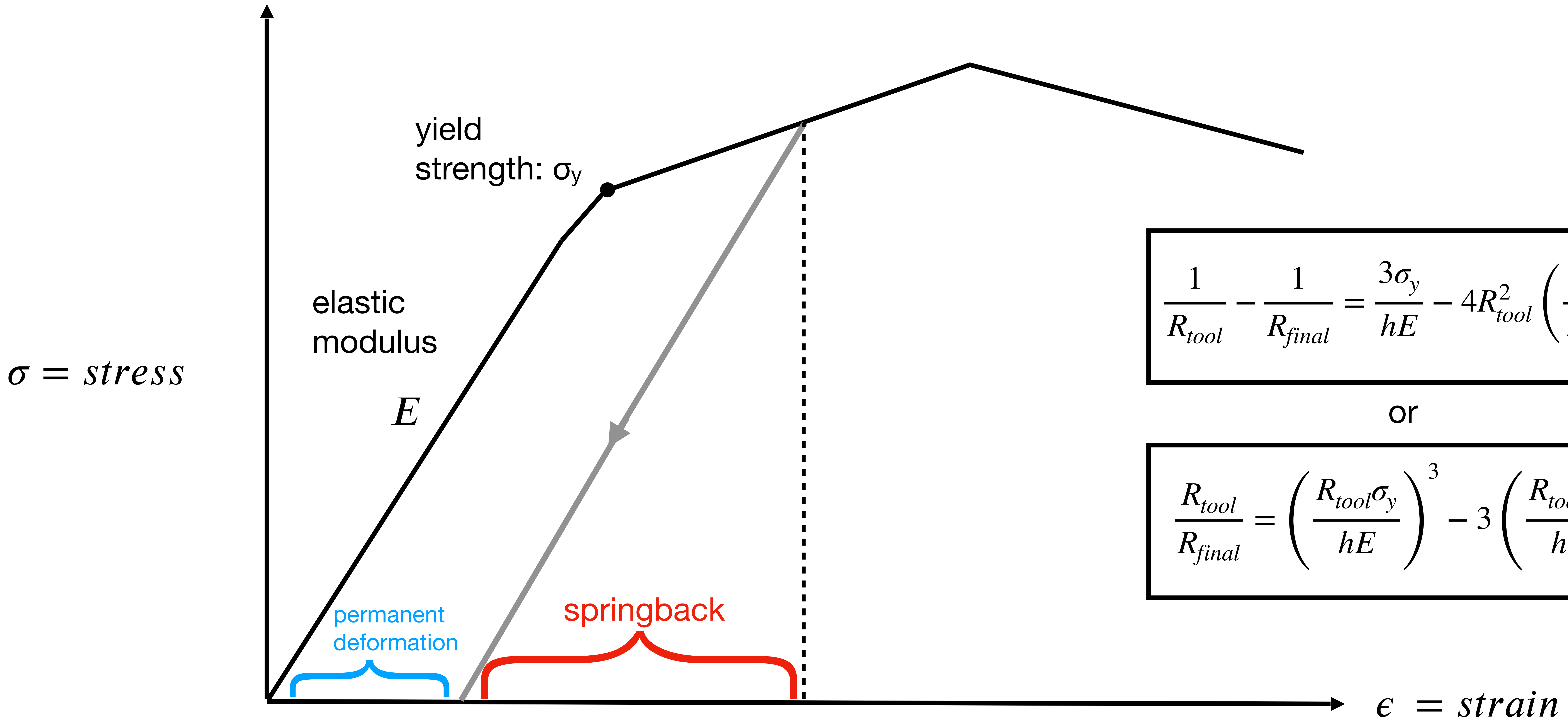
Sheet Metal Forming



Sheet metal concerns

- springback
- cracking

Sheet Metal Bending



$$\frac{1}{R_{tool}} - \frac{1}{R_{final}} = \frac{3\sigma_y}{hE} - 4R_{tool}^2\left(\frac{\sigma_y}{hE}\right)^3$$

what will the springback amount be?

(evaluate it or eliminate it)

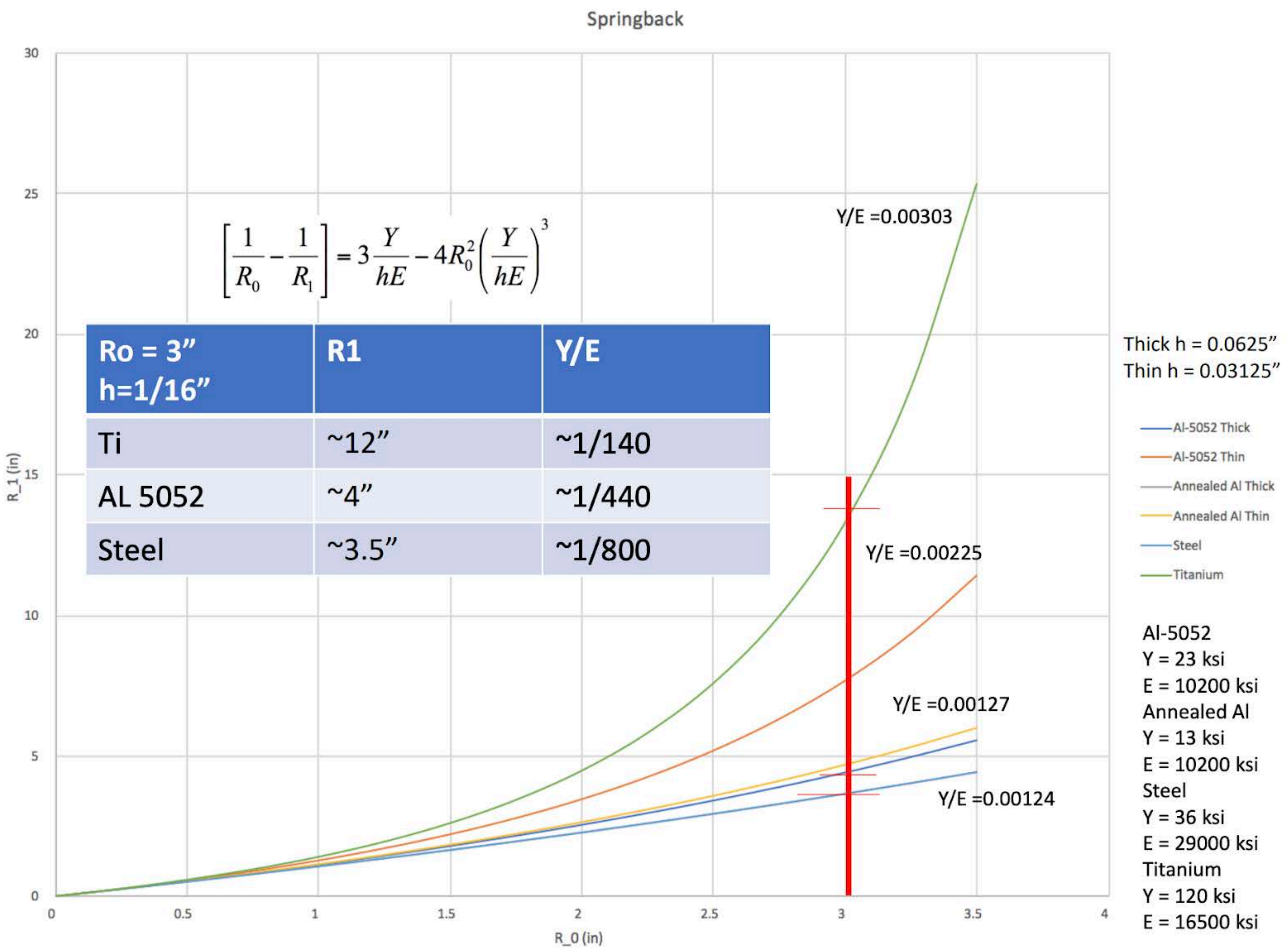
or

$$\frac{R_{tool}}{R_{final}} = \left(\frac{R_{tool}\sigma_y}{hE}\right)^3 - 3\left(\frac{R_{tool}\sigma_y}{hE}\right) + 1$$

what will the final radius be?

(predict final part)

Sheet Metal Bending



$$\left[\frac{1}{R_0} - \frac{1}{R_1}\right] = 3\frac{Y}{hE} - 4R_0^2\left(\frac{Y}{hE}\right)^3$$

Ro = 3” h=1/16”	R1	Y/E
Ti	~12”	~1/140
AL 5052	~4”	~1/440
Steel	~3.5”	~1/800

$R_1 = R_{final} = R_{unloaded}$ for various metals, treatments, and thicknesses

⚠️

$Y = \sigma_y$

$R_0 = R_{tool} = R_{loaded}$

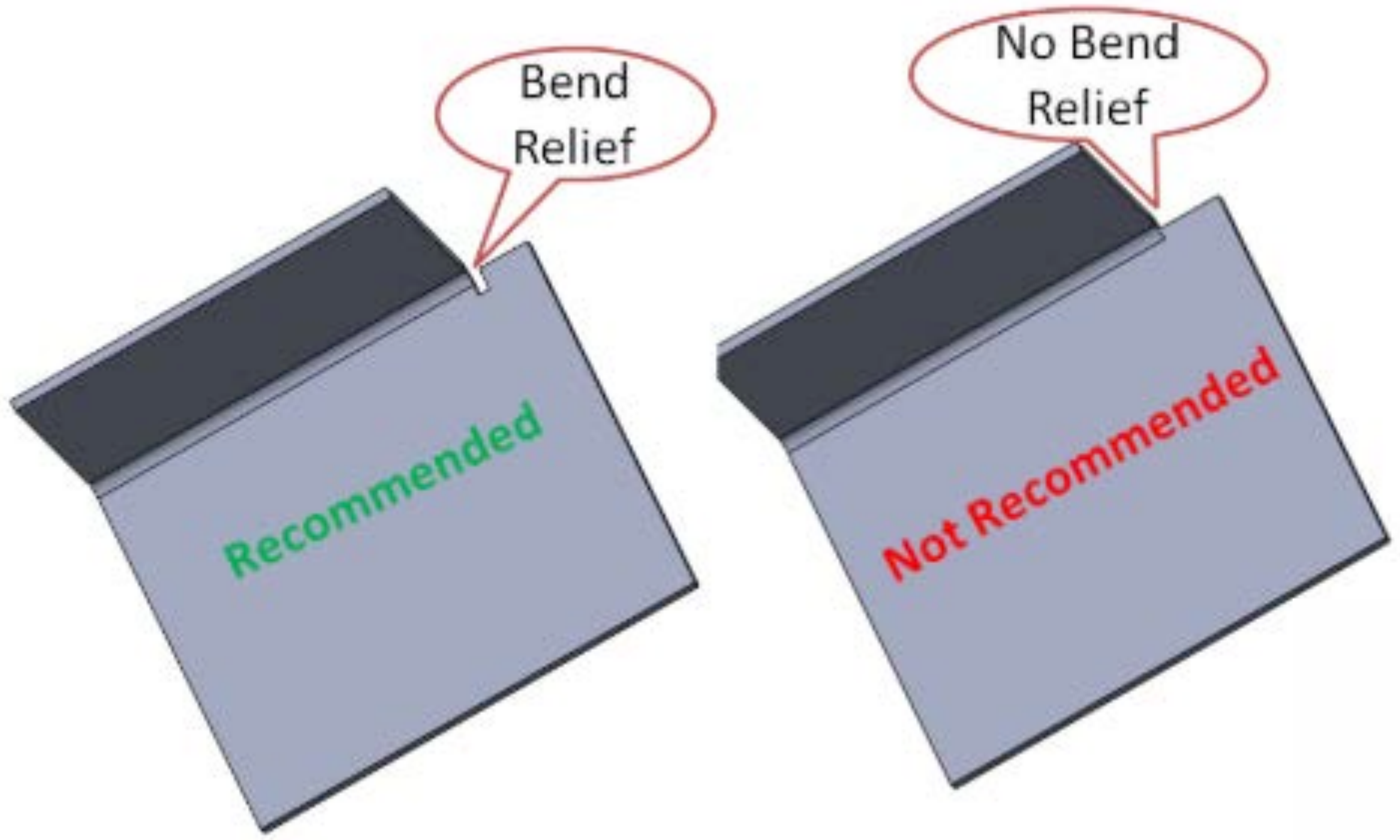
$R_1 = R_{final} = R_{unloaded}$

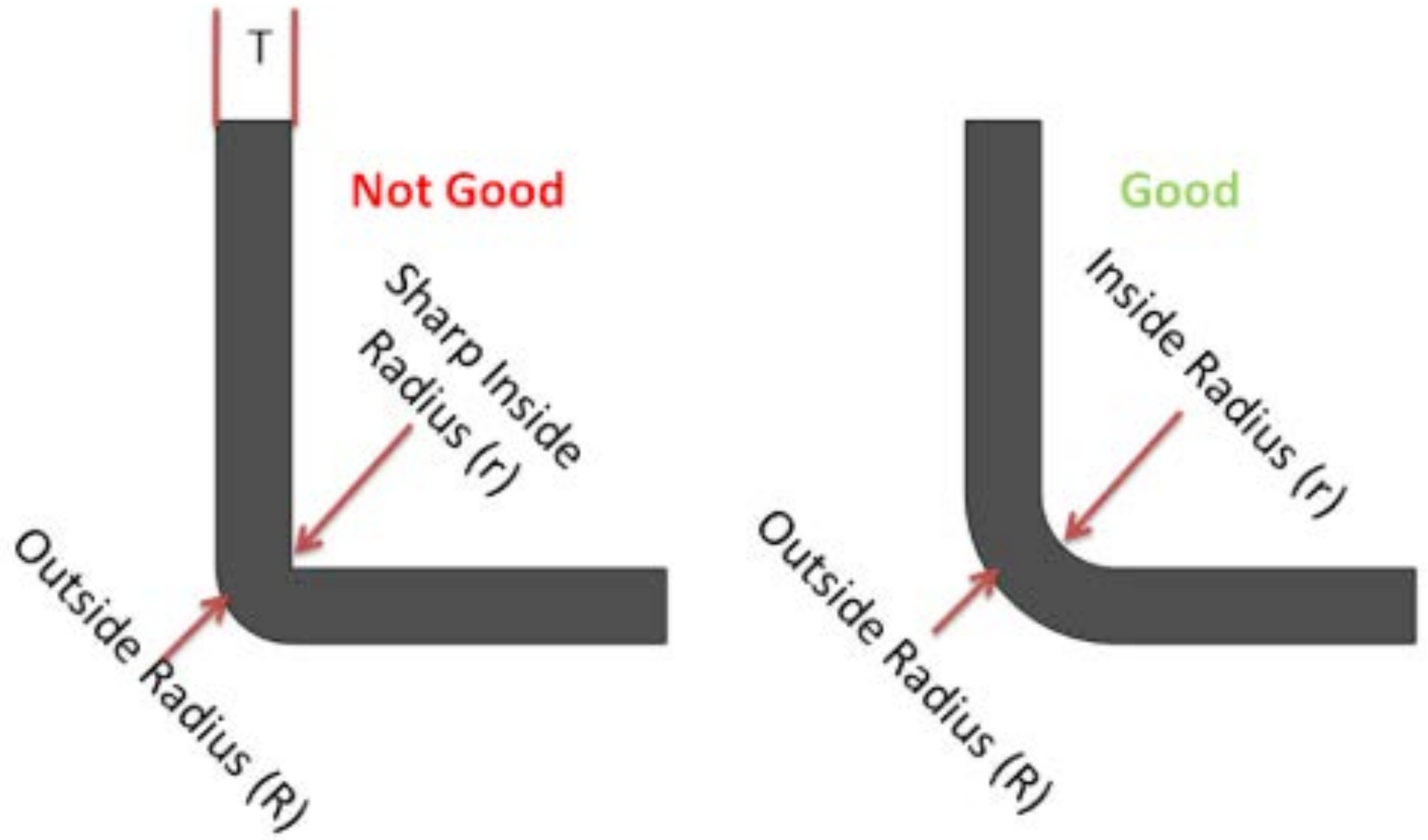
DFM for Sheet Metal

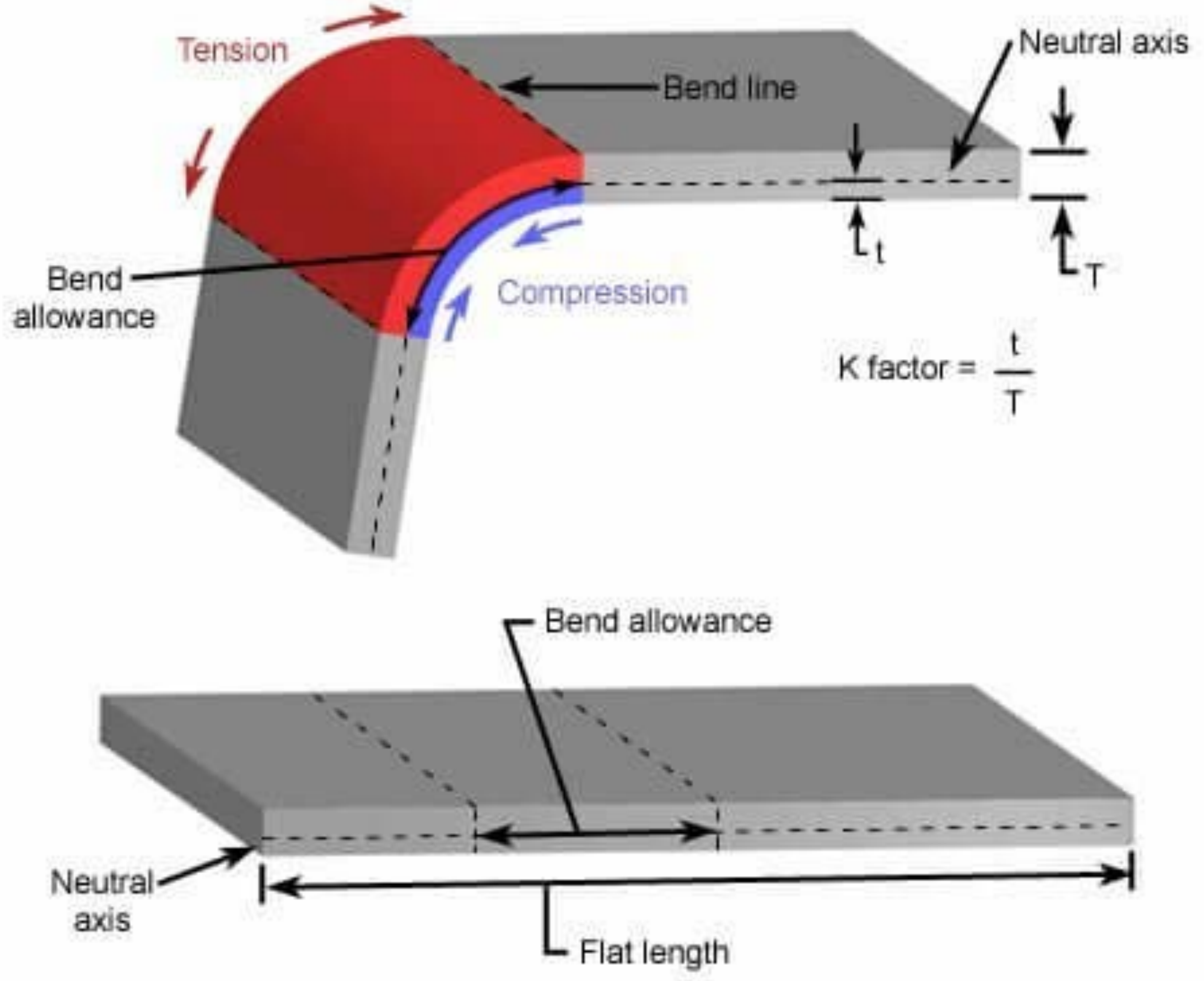
bending radii and allowances

springback: over-bend or stretch

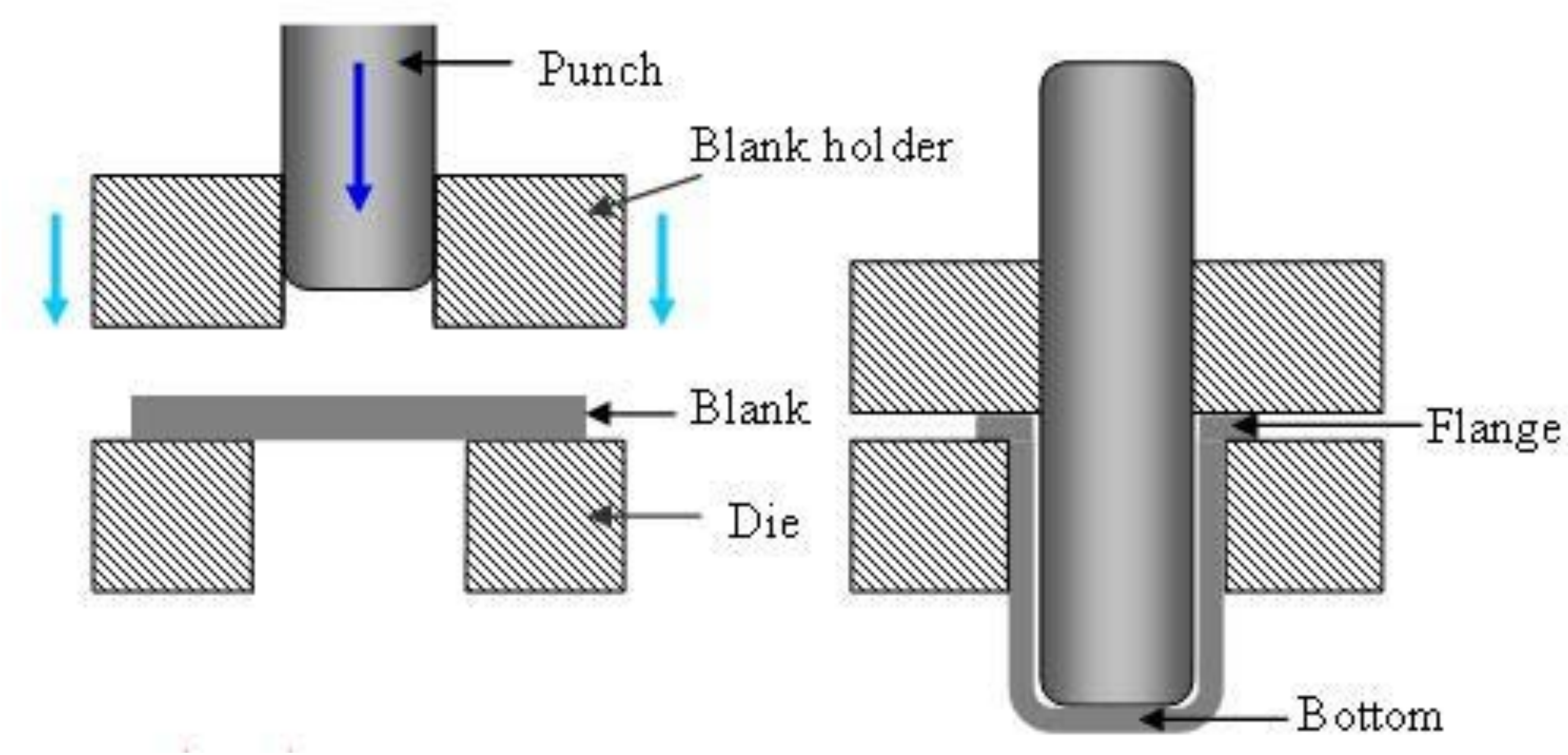
bend reliefs







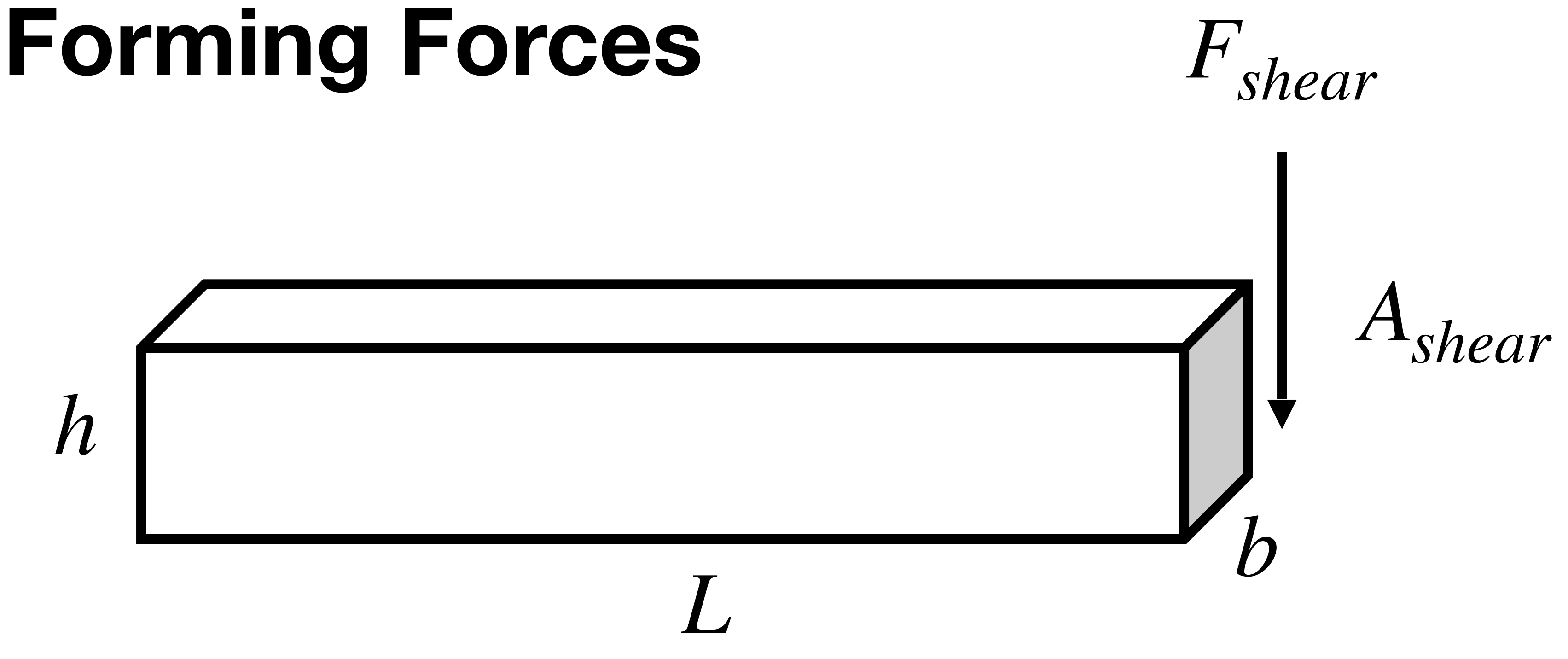
Stretching and Drawing



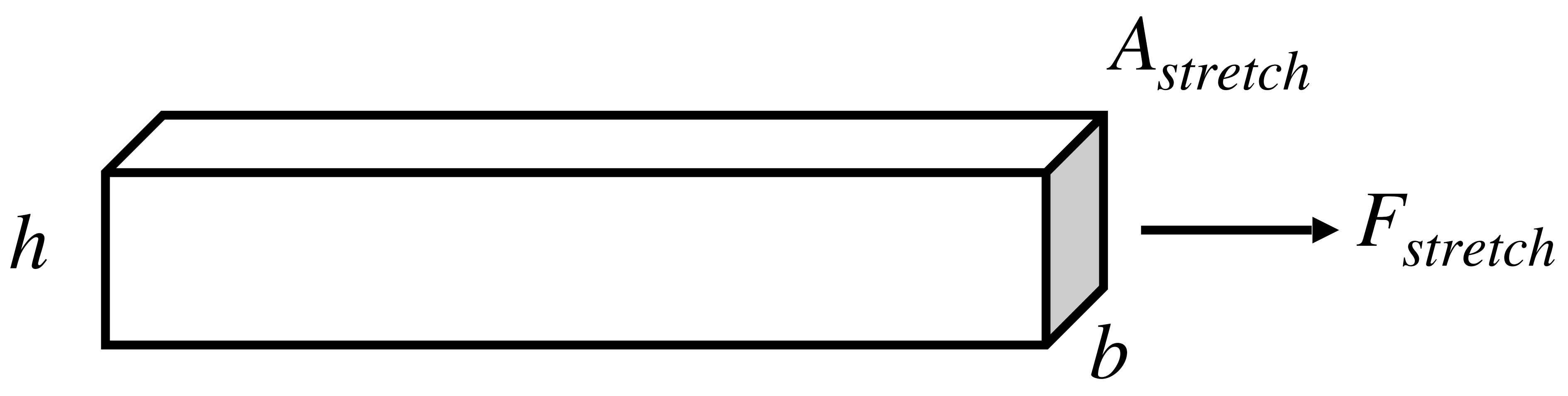
stretching: fix the flange and push down

drawing: do not fix flange

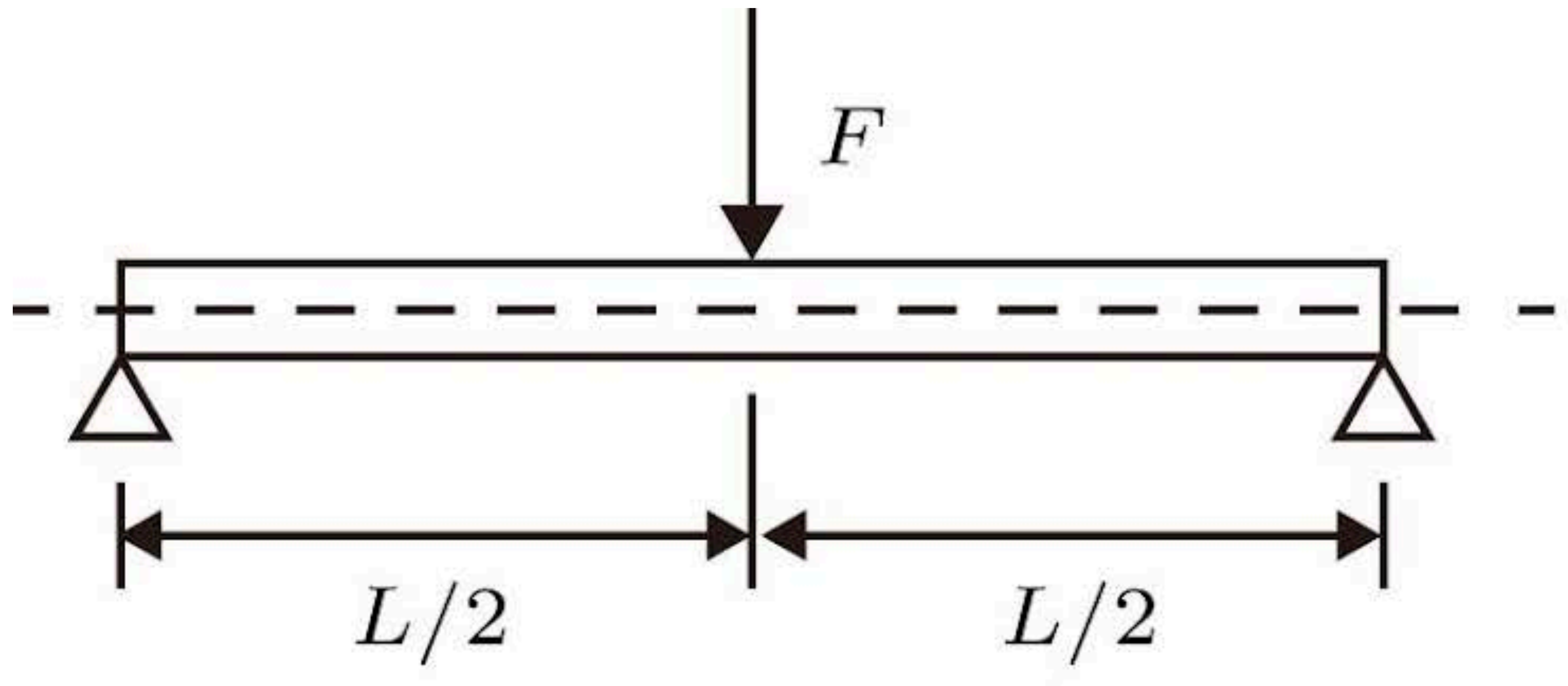
Forming Forces



$$F_{shear} = \sigma_{UTS} A_{shear} = \sigma_{UTS} bh$$



$$F_{stretch} = \text{"strength"} \cdot A_{shear} = \frac{\sigma_{UTS} + \sigma_y}{2} bh$$



$$F_{bending} = \frac{\sigma_y bh^2}{L}$$

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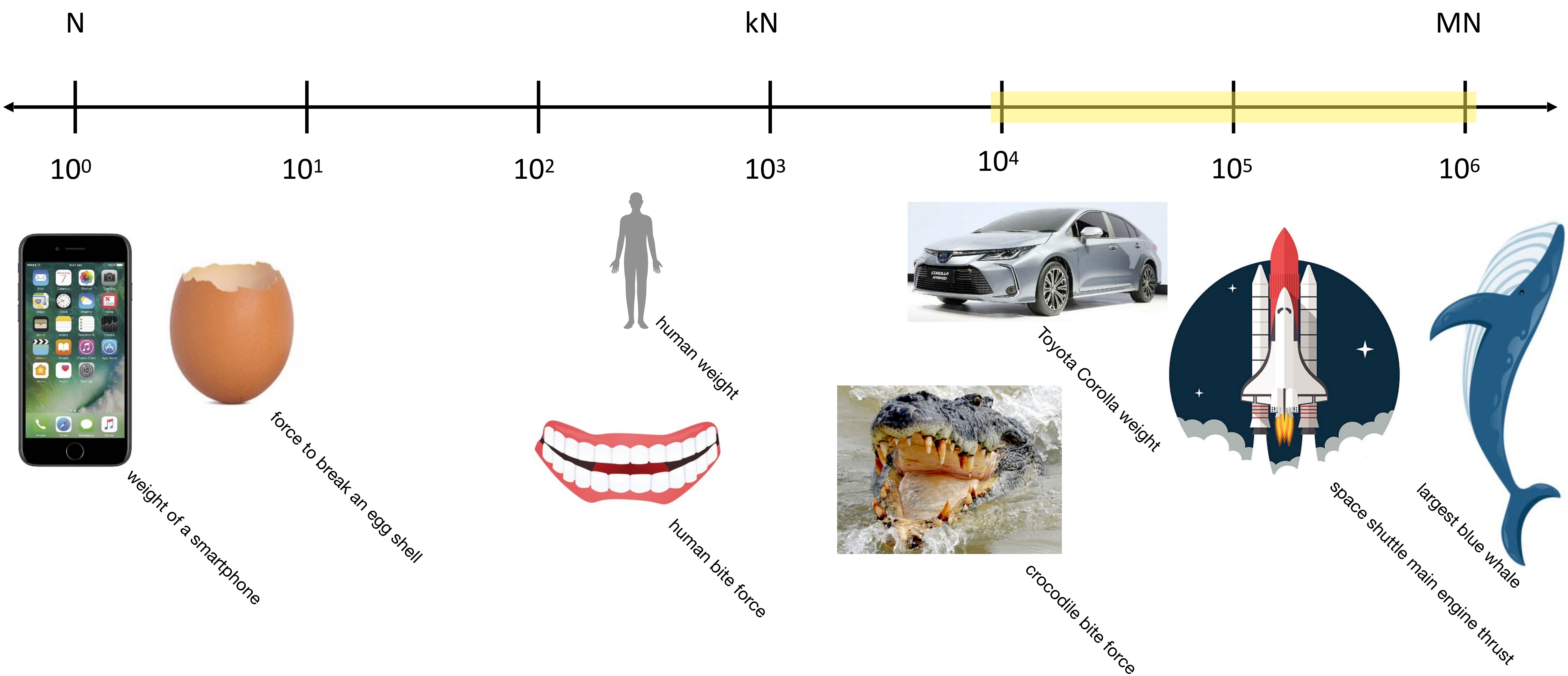

Rate/Cost/Quality/Flexibility

Advantages

- net shape process: rapid formation of part
- material properties are improved

Disadvantages

- high cost of equipment and dies
- limited flexibility of shapes and sizes
- accuracy/repeatability

Image Credits

Image Credits (cont.)

Slide 19:

Slide 20:

Slide 21:

Slide 22:

Slide 23:

Image Credits (cont.)