Tensile Coupon Test Lab

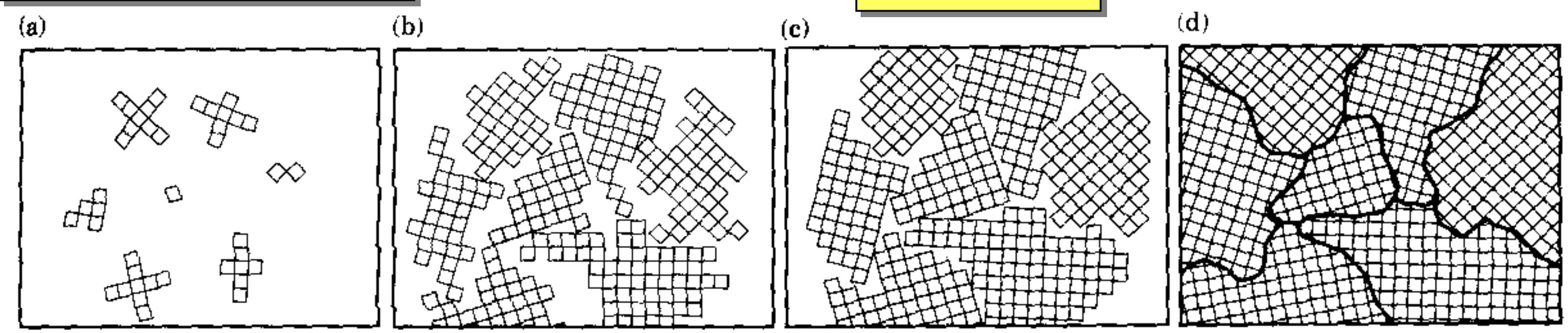
- Materials properties
  - *polycrystalline metals*
  - *isotropic vs anisotropic behavior*
  - *nonmetallic materials & composites*
- Mechanical properties of materials
- Testing machines

Solidification of Metals

- Nucleation
- Crystal growth
- Grain formation
- RESULT: polycrystalline material

Nucleation begins at foreign particles in melt

Interference develops



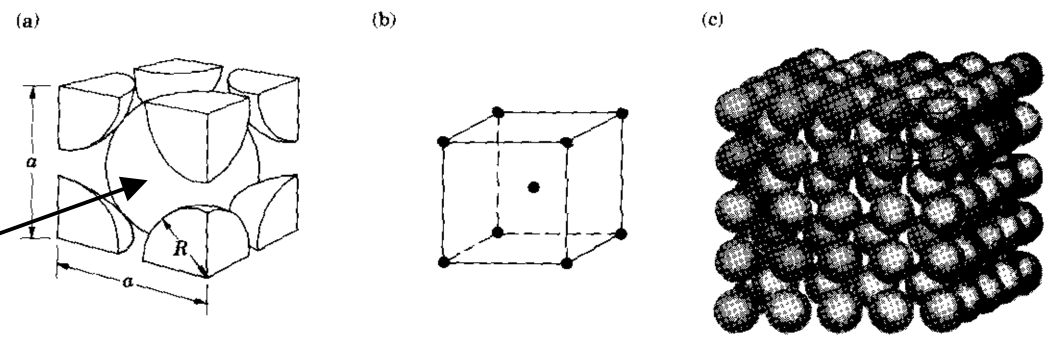
Crystals begin to grow from each

Result is grain structure with each grain having different crystal orientation

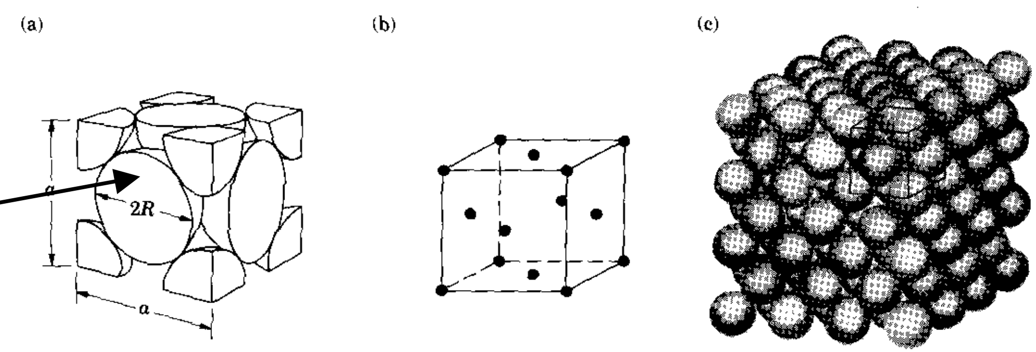
Deformation of a Crystal Structure

- Grains have a specific crystal structure that depends on the material and the conditions
  - *cubic*
  - *body centered cubic*
  - *face centered cubic*
  - *hexagonal*
  - *etc.*

Total of 2 atoms per each unit cube

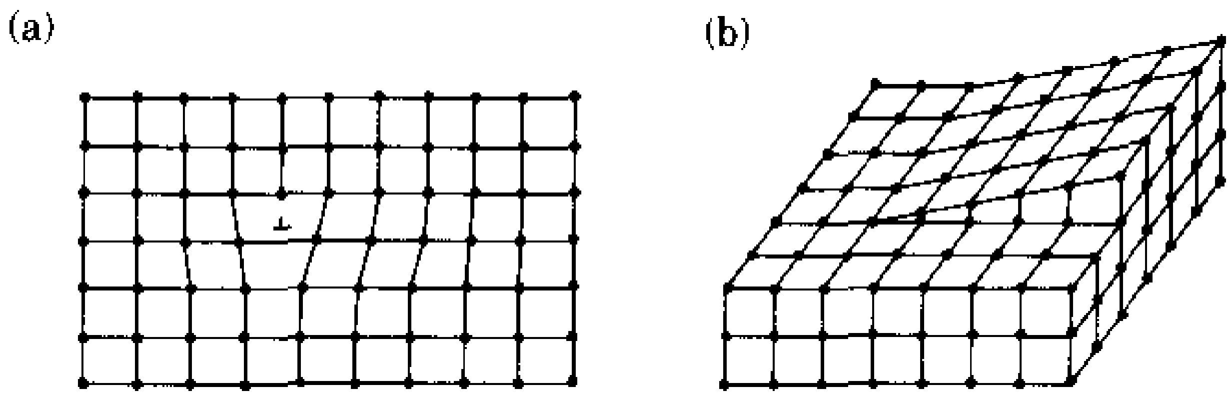


Total of 3 atoms per each unit cube



Crystal Deformation

- Dislocations
  - *result of flaws in crystal structure*
  - *results in deformation with relatively little effort*
  - *dramatically weaken the strength*

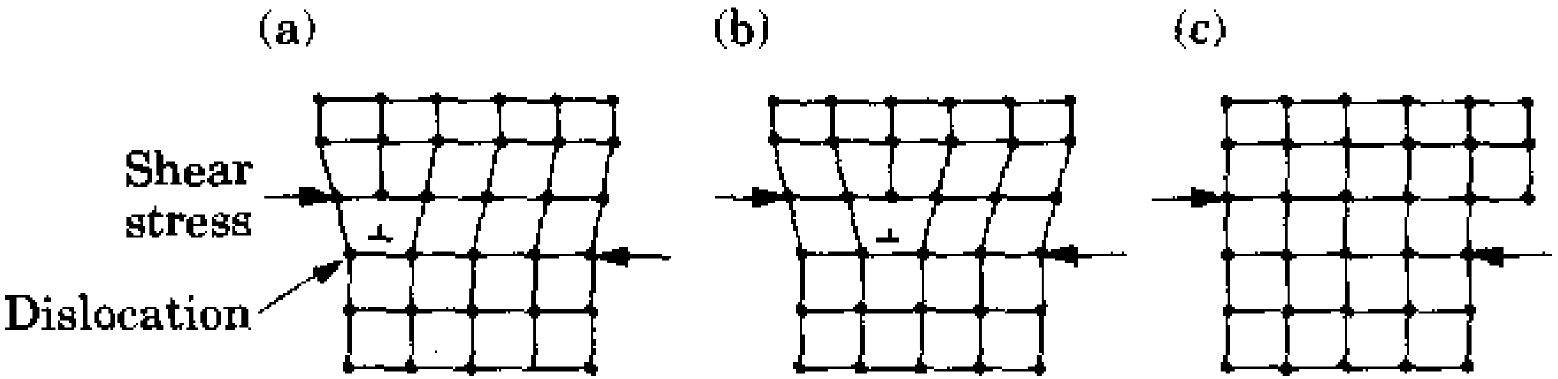


Edge dislocation **Screw dislocation**

Computations of Young's Modulus (E) from elasticity of lattice structure yield values that are way too high compared to measruements. Instead, crystal defects like dislocations result in a crystal that is much easier to deform and therefor yields a lower modulus.

Dislocation Movement Causes Crystal Deformation

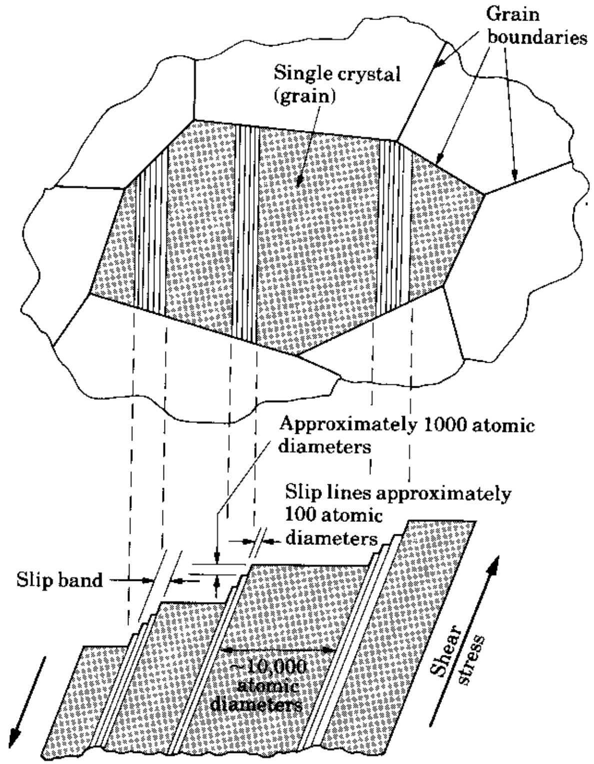
- Dislocations “move” through the crystal lattice with relatively little effort needed
- Only a few lattice bonds must be broken and restored for significant deformation to occur.



- Dislocations that are perpendicular to each other can run into each other and become “pinned”
  - *increases the apparent stiffness*
  - *may break free at high stress levels*
  - *this is thought to cause the upper/lower yield points for steels*

Slip Bands

- Crystal lattice can deform by breaking and reforming bonds along a plane called a slip plane
- Crystal structures may have several different slip bands



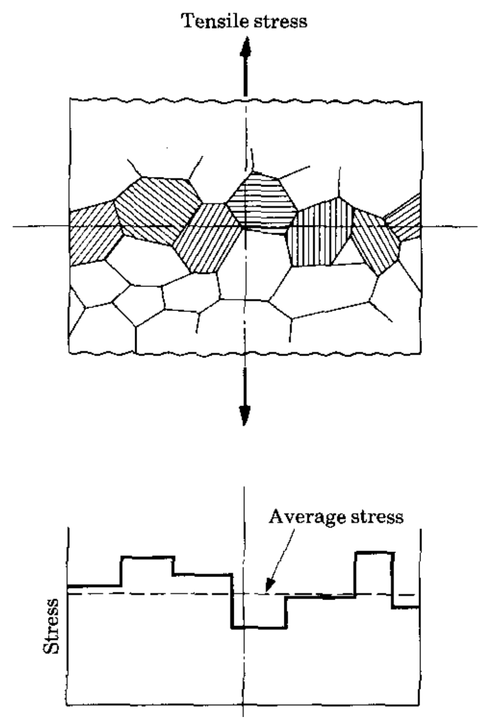
- When slip bands result in a mirror image of the original lattice, the slip process is called “twinning” (tin exhibits this with an audible clicking)

Metals and Alloys

- Pure metals are rarely used in engineering because they do not exhibit the most desirable properties
- Alloys are combinations of 2 or more metals
  - *solid solutions*
  - *intermetallic compounds*
- Example:
  - *pure iron is too soft and weak for engineering use*
  - *when carbon is disolved in iron: STEEL*
  - *amount of carbon and how it is worked can have profound impact on the mechanical properties of steels*
- Example:
  - *pure aluminum is far too soft for engineering use*
  - *when alloyed with magnesium, copper, zinc, etc. the result is a much stronger material*
  - *alloys are 2000, 4000, 6000, 7000, 8000 series*
  - *2024-T3 or 7075-T6 are common aircraft alloys (T indicated heat treatment)*
  - *6061 alloys are weldable and corrosion-resistant*

Directional Behavior

- When grains have purely random orientation and uniform size, the material mechanical properties are independent of loading direction: ISOTROPIC behavior



- Materials with directional dependency: ANISOTROPIC materials

Isotropic vs Anisotropic Behavior

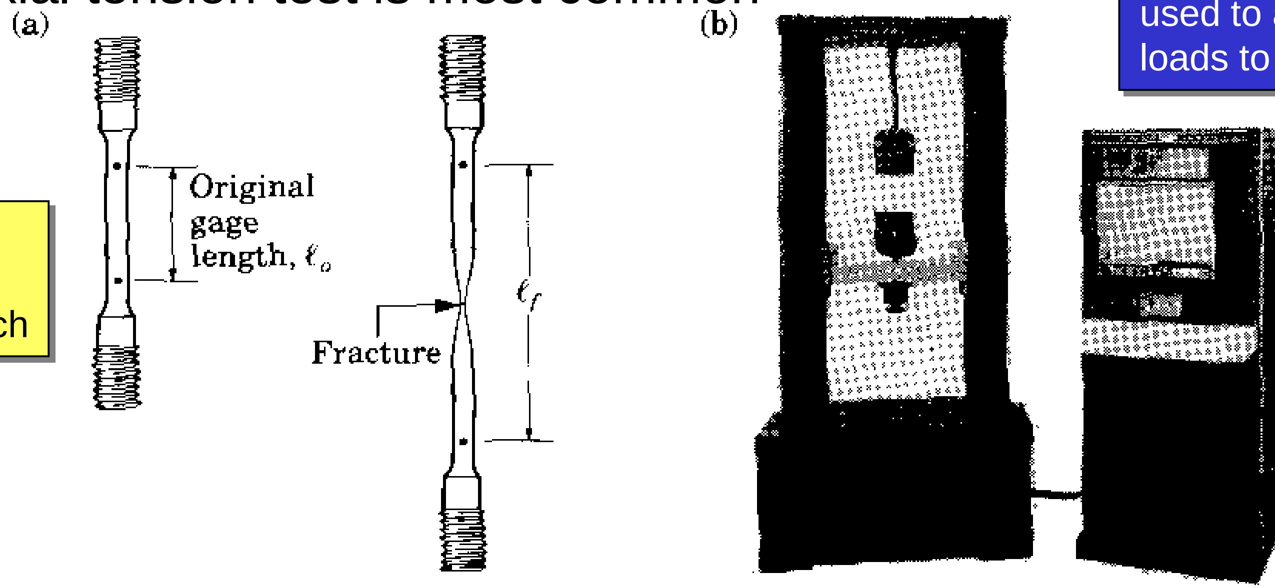
- Most metal alloys are isotropic to begin
  - *anisotropic behavior can be induced by deforming the alloy to change the grain structure and orientation*
  - *cold working, forging, etc. are examples*
  - *Example: titanium alloy billets are forged and then machined to form the frames for the F-16 fuselage.*
- Composite materials are heterogeneous combinations of 2 or more materials (e.g., carbon fibers in a resin matrix)
  - *composites are highly anisotropic and can be designed to enhance certain of these properties*
  - *natural materials like wood are also anisotropic (orthotropic)*

Material Testing

- Material properties are highly dependent on the type and composition as well as ageing and test environment
- Mechanical tests must be used to measure the mechanical properties since they cannot be directly computed from atomic level properties.
- Uniaxial tension test is most common

Test Machines are used to apply tensile loads to samples

Sample or “coupon” taken from larger batch



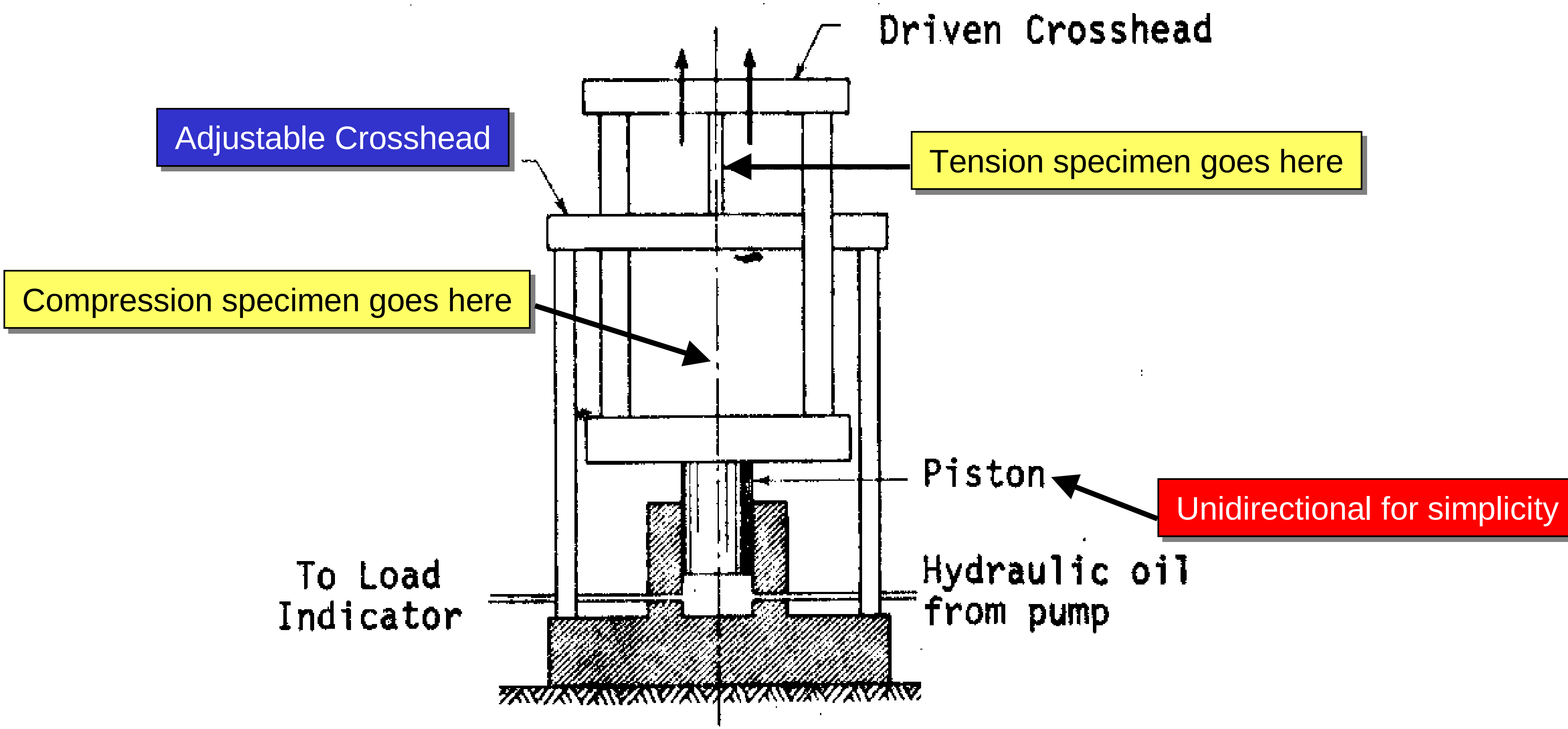
Test Machines

- Loading systems
  - *uniaxial (single applied force in a fixed direction)*
  - *biaxial (orthogonal forces or a force and a torsion load)*
- Loading rates
  - *static or quasi-static*
  - *dynamic (cyclic or random)*
- Load generation
  - *mechanical screw-jacks*
  - *hydraulic pistons*
  - *servo-controlled hydraulic pistons (servohydraulic system)*
  - *other (e.g., thermal expansion, piezoelectric deformation)*
- Load weighing

See class notes for details

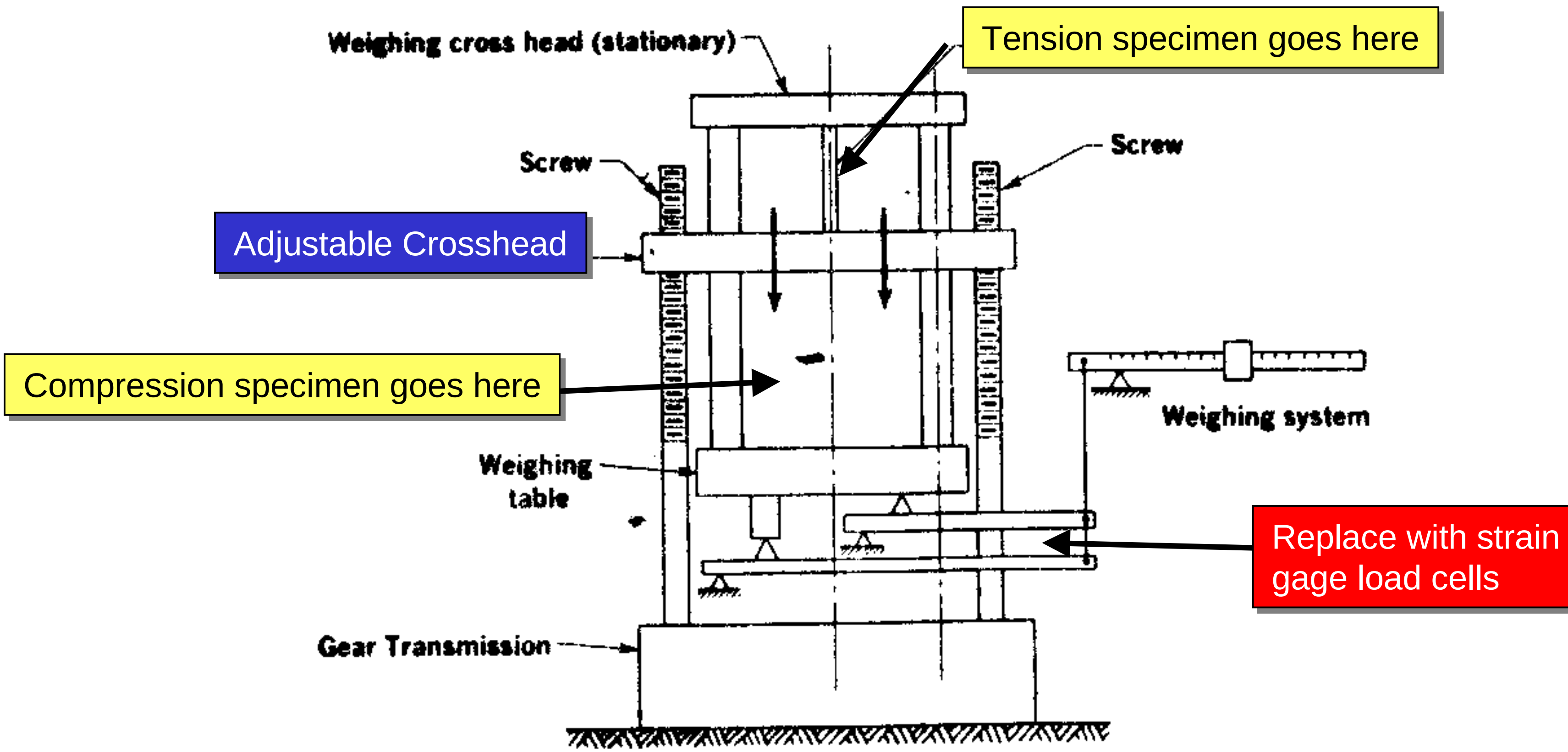
Hydraulic Universal Test Machine

- This is the "classic" testing machine
  - *capable of applying either tension or compression*
  - *static or very slow loading rates*



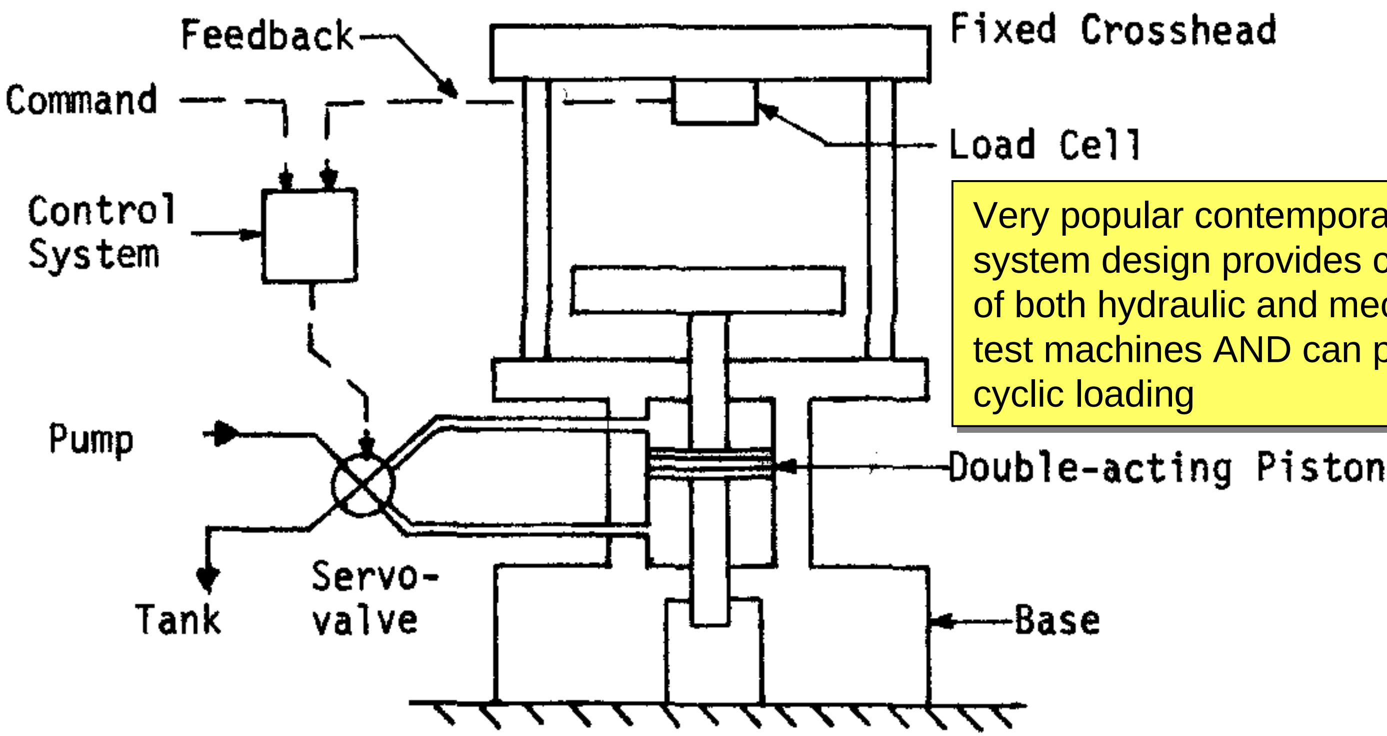
Mechanical Test Machine

- Screw-jack system drives a crosshead up or down
- Load is sensed by a separate load cell
- Example: Instron Test Machine in AE3145 Lab



Servo-hydraulic Test Machine

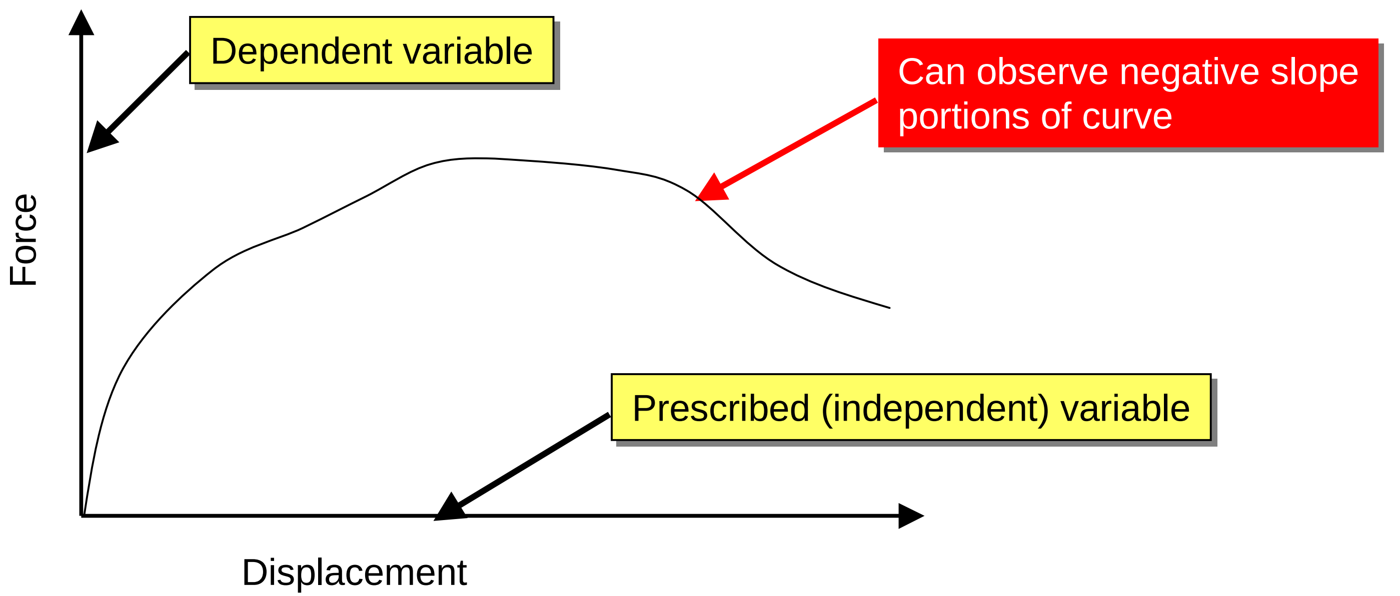
- Uses output feedback control system with hydraulic servo-valve to control movement of an hydraulic actuator (piston & cylinder)
- Feedback:
  - *Force from load cell: <u>Force Control</u> (like hydraulic test machine)*
  - *Piston displacement: <u>Displacement Control</u> (like mech. test machine)*



Very popular contemporary system design provides characteristics of both hydraulic and mechanical test machines AND can produce cyclic loading

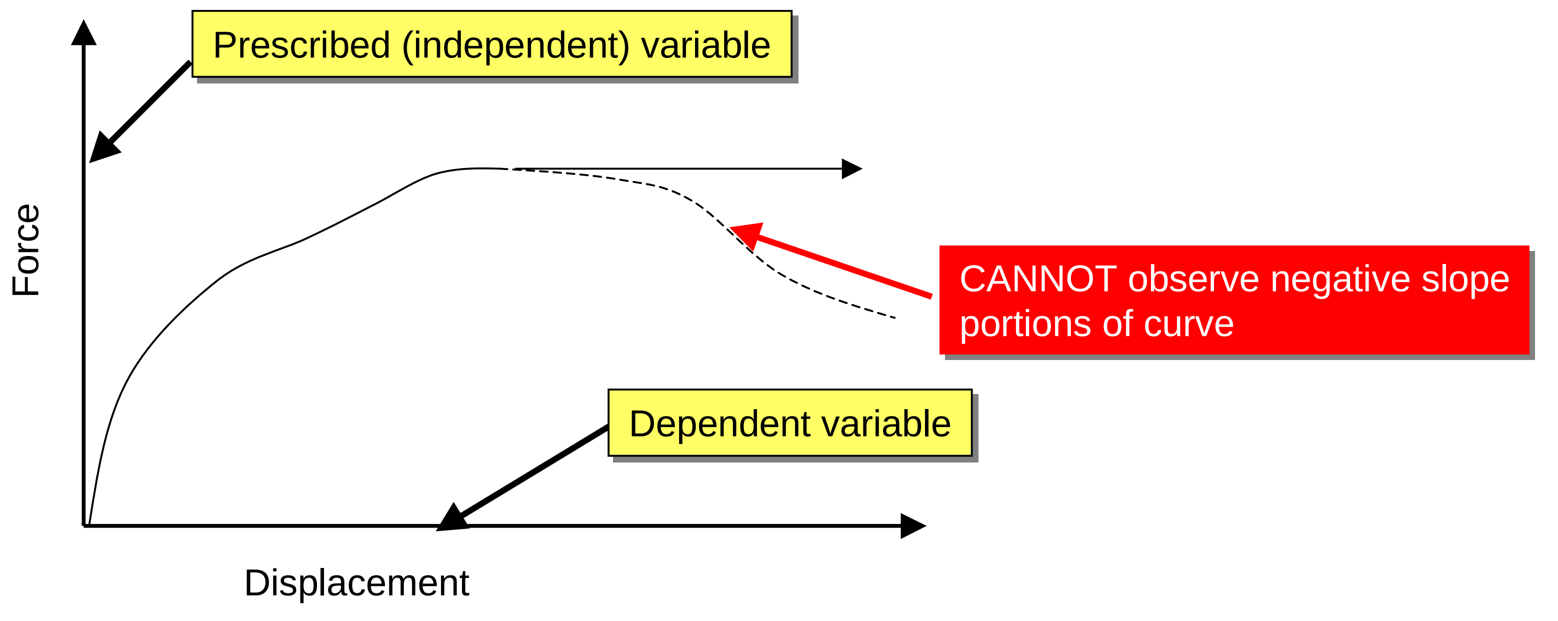
Test Machine Characteristics

- Load-deflection behavior is defined by the kind of test machine that is employed.
- Mechanical:
  - *prescribed displacement*
  - *resulting force depends on specimen stiffness:* $F = k_S d$



Hydraulic Test Machine

- Load-deflection behavior is defined by the kind of test machine that is employed.
- Hydraulic:
  - *prescribed force*
  - *resulting displacement depends on specimen stiffness:* $d = k_S / F$

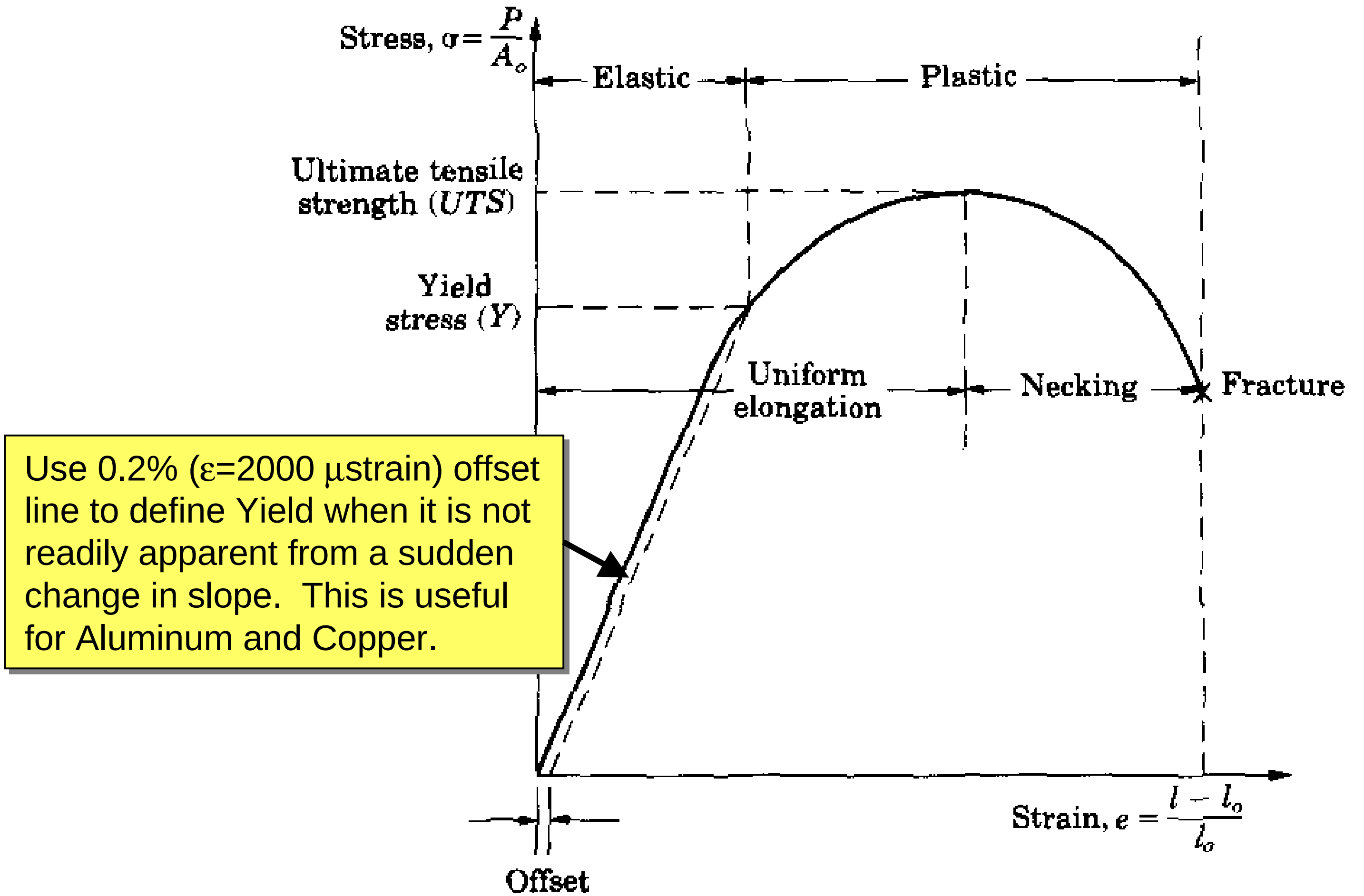


Other Comments on Test Machines

- Servohydraulic test machines:
  - *Behave like mechanical machines when operated in displacement control mode.*
  - *Behave like hydraulic machines when operated in force control mode.*
- Test machines may experience considerable elastic deformation themselves, especially at high load levels
  - *strain energy is stored in the elastic deformation of the frame*
  - *this can be explosively released when a specimen suddenly fails*
  - *can cause machine to "jump" or pieces of the failed specimen to be forcefully ejected from the test machine!*
  - *mechanical machines are more immune to this but are usually much slower and not easily controlled*

Mechanical Test Results

- Stress-strain results:
  - *Engineering stress & strain are based on initial cross section area, A_0, and an initial strain gage base length, L_0*



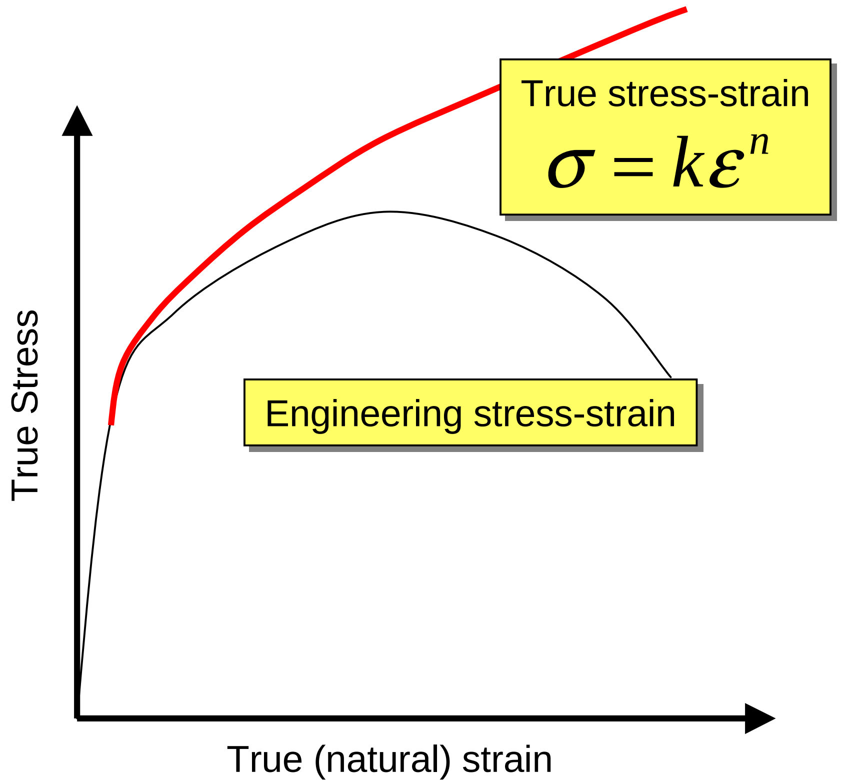
Typical Values for E, Yield & Ultimate Stress, Elongation

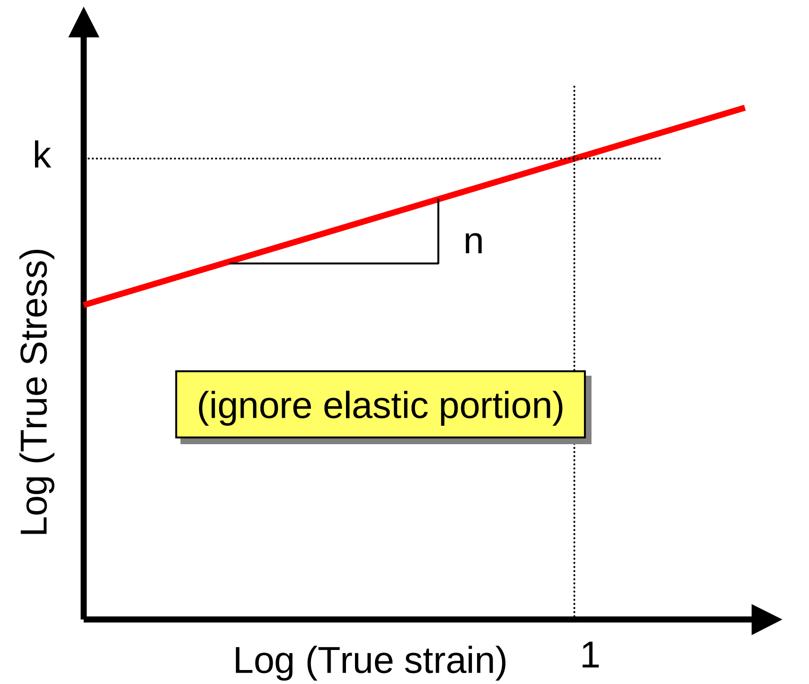
METAL	E (GPa)	Yield (MPa)	Ultimate (MPa)	Elongation (%)
Aluminum	69	35	90	45
Aluminum alloys	69-71	35-550	90-600	45-4
Beryllium	-	185-260	230-350	3.5-1
Copper	105	70	220	45
Copper alloys	105-150	76-1100	140-1310	65-3
Iron	-	40-200	185-285	60-3
Steels	190-200	205-1725	415-1750	65-2
Lead	14	7-14	17	50
Lead alloys	14	14	20-55	50-9
Magnesium	41	90-105	160-195	15-3
Magnesium alloys	41-45	130-305	240-380	21-5
Molybdenum alloys	325	80-2070	90-2340	40-30
Nickel	180	58	320	30
Nickel alloys	180-214	105-1200	345-1450	60-5
Tantalum alloys		480-1550	550-1550	40-20
Titanium	80	140-550	275-690	30-17
Titanium alloys	80-130	344-1380	415-1450	25-7
Tungsten	400	550-690	620-760	0

NON-METALS	E (GPa)	Yield (MPa)	Ultimate (MPa)	Elongation (%)
Acrylics	1.4-3.4			
Epoxies	3.5-17		35-170	0
Nylons	1.4-2.8		7-80	5-100
Plastics (reinforced)	2-50		200-520	0
Glass	70-80		140	0
Diamond	820-1050			
Graphite	240-390		2100-2500	0

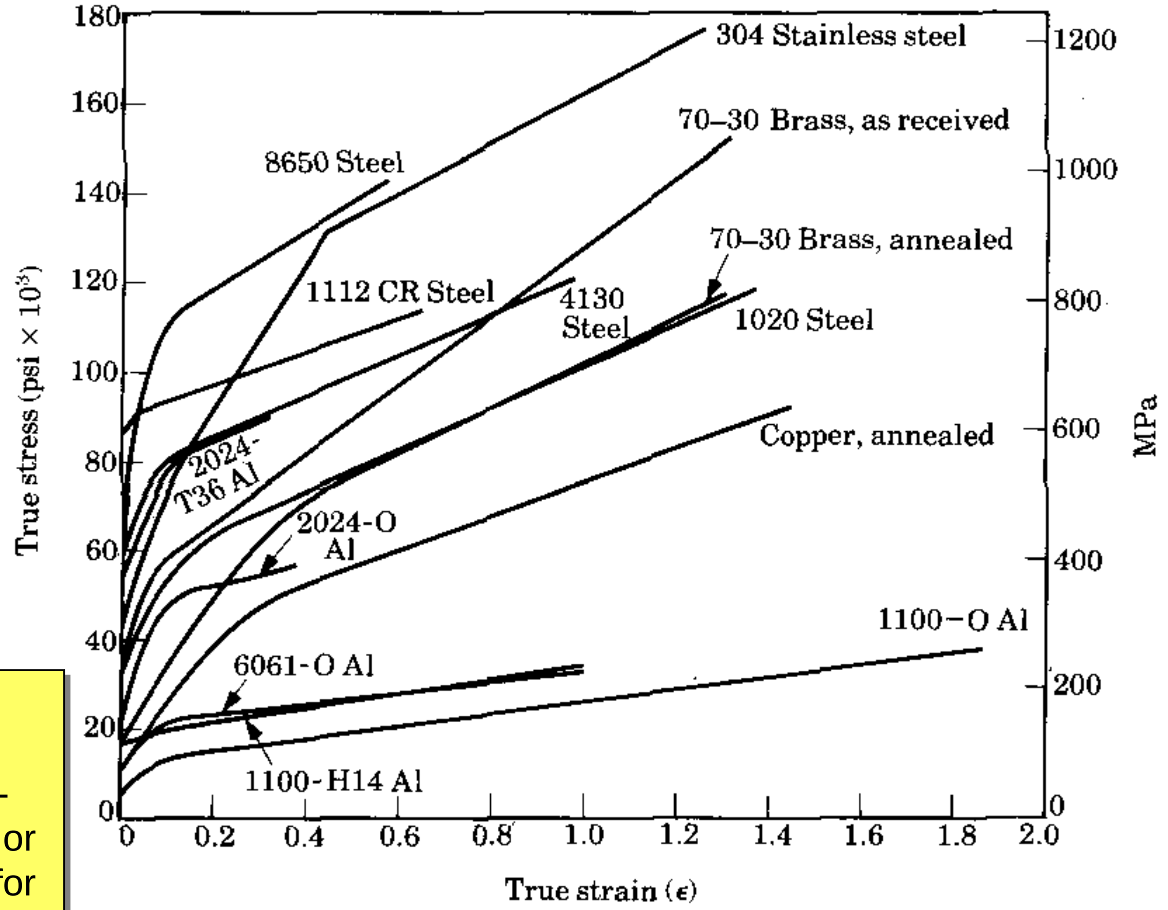
True Stress-Strain Behavior

- True stress: σ=P/A where A=instantaneous cross section
- True strain: $$d\varepsilon = \frac{dL}{L} \ and \ \varepsilon = \int_{L_0}^{L} d\varepsilon = \ln\frac{L}{L_0}$$





Example True Stress-Strain Curves



For Al alloys, -O means fully annealed (soft); -Txx means heat or solution treated for enhanced strength

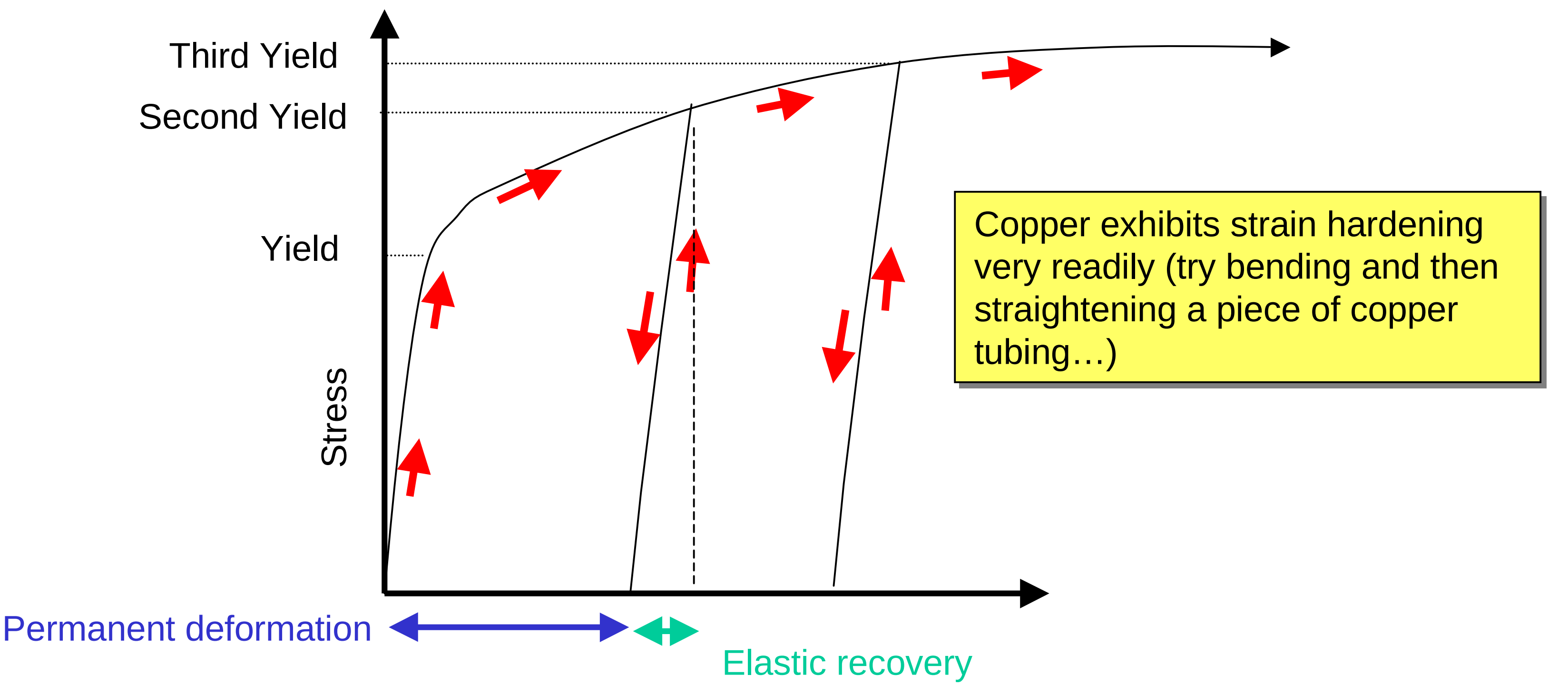
Typical Values for K and n (Room Temperature)

Can show that true strain at onset of necking is numerically equal to value of n. Relatively large values of n mean material can sustain large strain before necking (and failure).

MATERIAL	k (MPa)	n
Aluminum		
1100-O	180	0.20
2024-T4	690	0.16
6061-O	205	0.20
6061-T6	410	0.05
7075-O	400	0.17
Brass		
70-30 annealed	900	0.49
85-15 cold rolled	580	0.34
Copper (annealed)	315	0.54
Steel		
Low carbon, annealed	530	0.26
4135 annealed	1015	0.17
4135 cold rolled	1100	0.14
4341 annealed	640	0.15
304 stainless, annealed	1275	0.45
410 stainless, annealed	960	0.10

Strain Hardening

- Load into the plastic region…
- Unloading will follow a line parallel to elastic load line…
- Repeated loading will follow unloading line to plastic line and continue deformation.
- Material appears to be stronger (higher yield):



Other Effects

- Cyclic loading can produce fatigue failures
  - *failure can occur even when cyclic stresses never exceed the yield stress for the material (called high cycle fatigue because it usually requires millions of cycles)*
  - *Endurance Limit: stress level below which fatigue never occurs.*
  - *low cycle fatigue occurs when stresses reach or exceed yield for each cycle of loading*
  - *failure depends on the loading history*
  - *mean stress level and stress amplitude affect the number of cycles to failure (use an S-N diagram)*
- Creep is time-dependent inelastic strain when stress is applied
  - *creep is highly dependent on temperature*
  - *can occur at room temperature for plastics*
- Impact
  - *susceptibility to fracture under sharp loading*
  - *often an issue for composites*
- Ductility (amount of inelastic deformation that can be sustained)