IntroductiontoEngineeringMaterials

MechanicalProperties

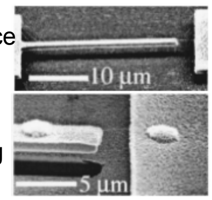
Whymechanical properties?

Needtodesignmaterialsthatcanwithstandappliedload…

e.g. materialsused in buildingbridges that can hold up automobiles, pedestrians

materialsfor skyscrapers intheWindy City…

materialsforspace exploration…



materials for and designing MEMsand NEMs…

Space elevators?

Issuestoaddress…

- Stressandstrain
- Elasticbehavior
- Plasticbehavior
- Strength,ductility,resilience,toughness,hardness
- Mechanicalbehaviorofdifferentclassesof materials
- Design/safetyfactors

Stressand Strain

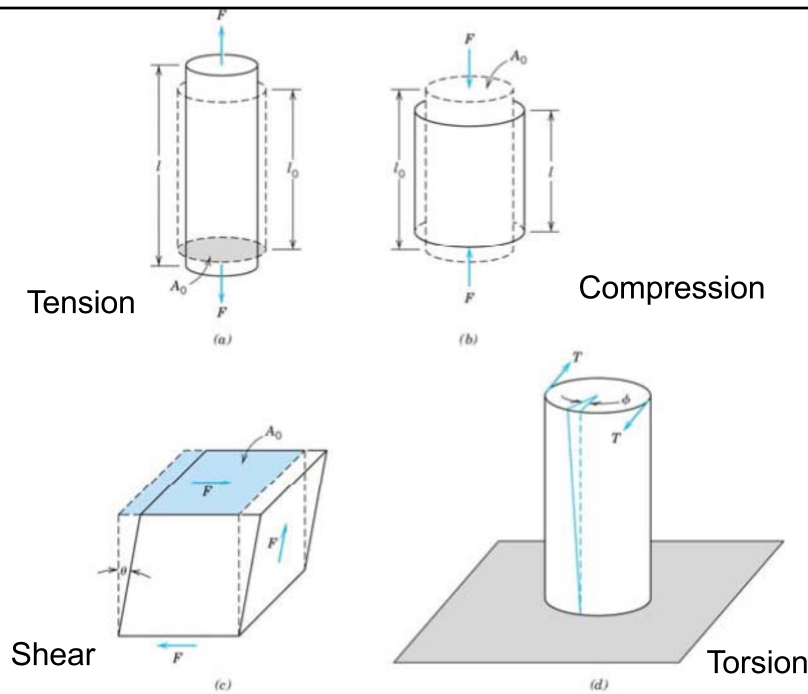
Stress: Pressuredue to appliedload.

tension,compression,shear, torsion, and combination.

$$stress = \sigma = \frac{forc}{eare}$$

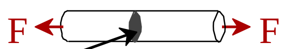
a

Strain:response ofthematerial tostress(i.e.physical deformationsuch as elongationdue to tension).



COMMONSTATESOFSTRESS

- Simpletension:cable



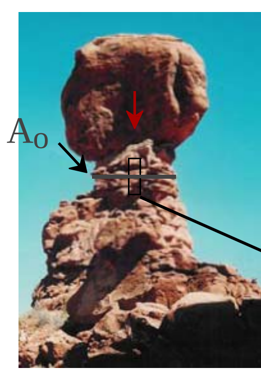
A_o= cross sectional
Area (when unloaded)

$$\sigma = \frac{F}{A_o}$$

Skilift(photocourtesyP.M.Anderson)

COMMONSTATESOFSTRESS

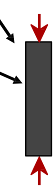
- Simplecompression:



Balanced Rock, Arches
National Park

Canyon Bridge, Los Alamos, NM

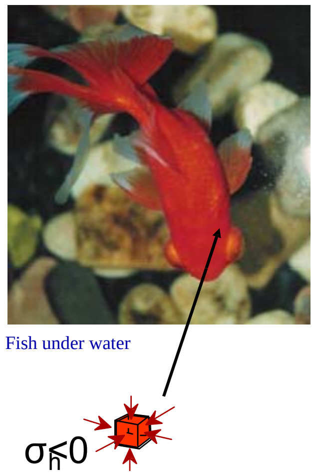
$$\sigma = \frac{F}{A_o}$$



Note:compressive
structuremember
(σ<0here).

COMMONSTATESOFSTRESS

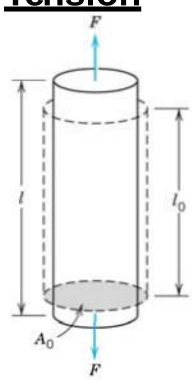
- Hydrostaticcompression:



Fish under water

TensionandCompression

Tension



Engineering stress= $\sigma = \frac{F}{A_o}$

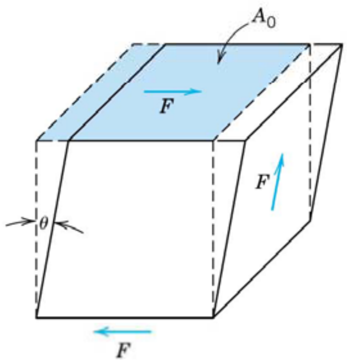
Engineeringstrain= $\varepsilon = \frac{l_i - l_o}{l_o} = \frac{\Delta l}{l_o}$

A_o=originalcrosssectionalarea
l_i=instantaneouslength
l_o=originallength
Note:strain is unitless.

Compression

Sameastensionbutintheoppositedirection(stressandstraindefined inthesamemanner).
Byconvention,stressandstrainarenegativeforcompression.

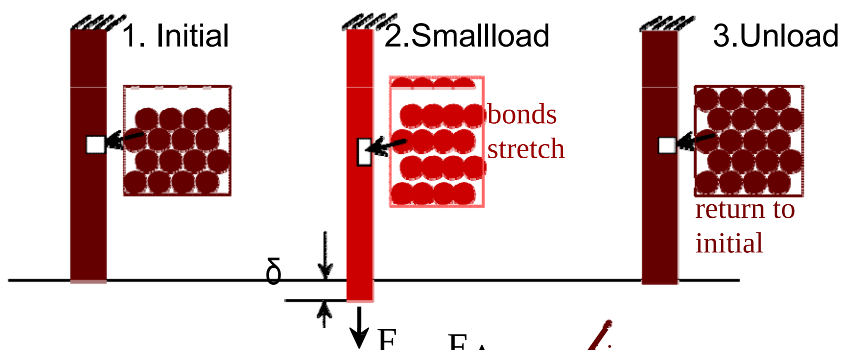
Shear

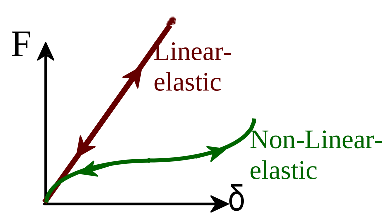


Pure shear stress = $\tau = \frac{F}{A_o}$

Pure shear strain = $\gamma = \tan\theta$

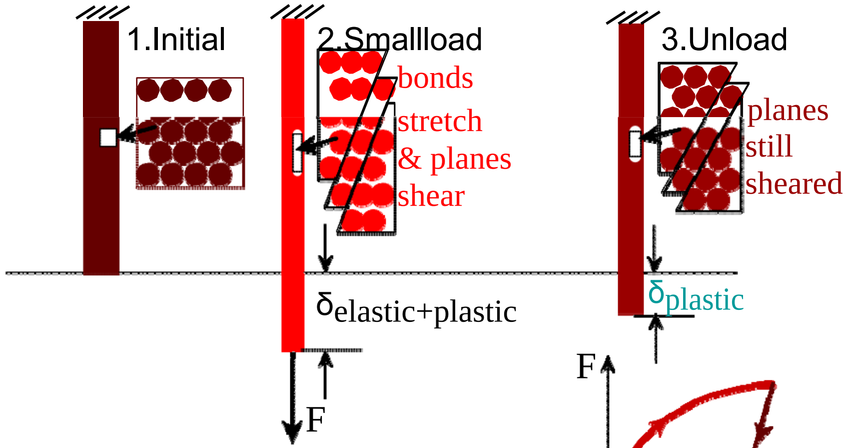
Elastic Deformation

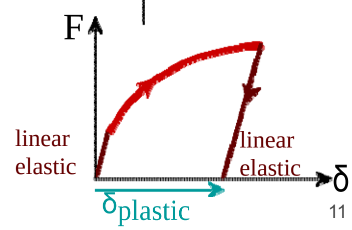




Elastic means reversible!

PlasticDeformation

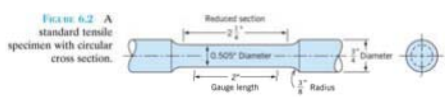




Plasticmeans permanent!

FromCallister6eresource CD.

Stress-straintest



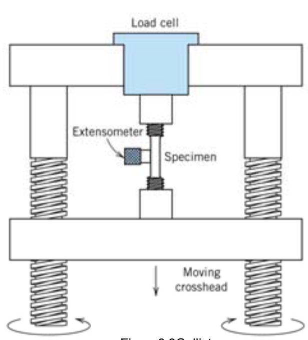
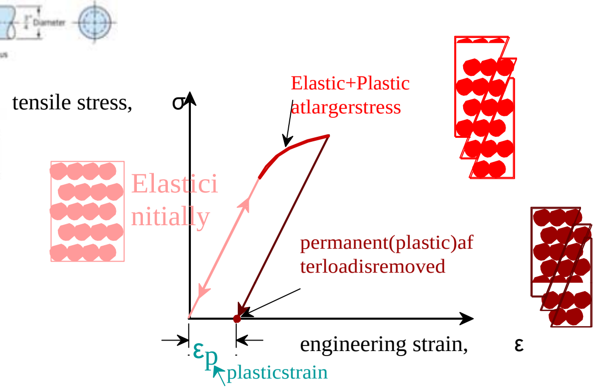


Figure6.3Callister



ElasticDeformation

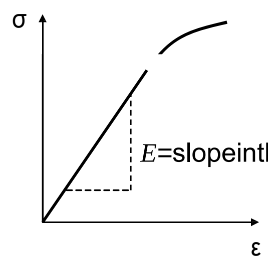
-anon-permanentdeformationwherethematerialcompletely recoverstoitsoriginalstateuponreleaseoftheappliedstress.

Hooke'sLaw: $\sigma = E\varepsilon$

stress → σ; strain → ε

Modulusofelasticity(Young'smodulus) → E

Measureofmaterial'sresistance toelasticdeformation(stiffness).



Formetals,typically E~45–400GPa

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Recall backto bondingEnergyvs.r curve…

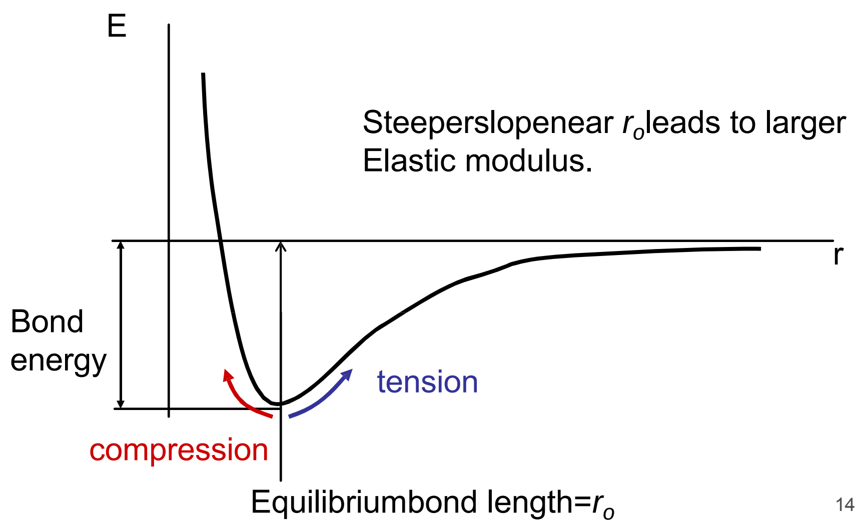

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Table 6.1 Room-Temperature Elastic and Shear Moduli, and Poisson's Ratio for Various Metal Alloys

Metal Alloy	*Modulus of Elasticity* *GPa*	*Modulus of Elasticity* *10^6 psi*	*Shear Modulus* *GPa*	*Shear Modulus* *10^6 psi*	*Poisson's Ratio*
Aluminum	69	10	25	3.6	0.33
Brass	97	14	37	5.4	0.34
Copper	110	16	46	6.7	0.34
Magnesium	45	6.5	17	2.5	0.29
Nickel	207	30	76	11.0	0.31
Steel	207	30	83	12.0	0.30
Titanium	107	15.5	45	6.5	0.34
Tungsten	407	59	160	23.2	0.28

Silicon(singlecrystal)	120-190(dependsoncrystallographicdirection)
Glass(pyrex)	70
SiC(fusedorsintered)	207-483
Graphite(molded)	~12
HighmodulusC-fiber	400
CarbonNanotubes	**~1000**

Ifwenormalizetodensity:~20times thatofsteelwire.
Densitynormalizedstrengthis~56X thatofsteelwire.

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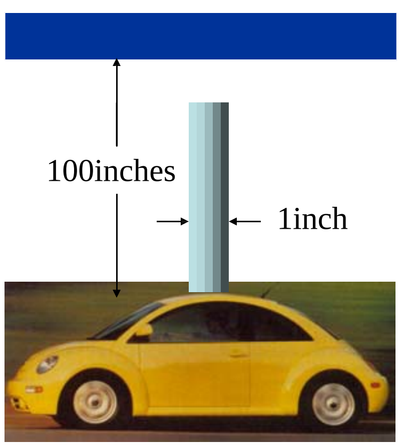
Elasticdeformation:exampleproblem



MATSE 101MaterialsinToday's World © I. Robertson, Ken Bratland1999,2000

©Tim Spila,2002

Steelcarhanger: Howmany VWBeetles mustwehang froma 100 inch longbar ofsteelin ordertostretchitby 1%?

A_o=1 in^2
E=30 x 10^6psi

Will this be an elastic deformation?

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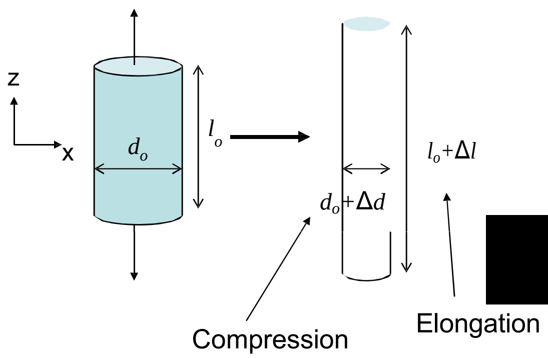
PoissonRatio

Sofar,we'veconsideredstressonlyalongonedimension…



Alongz:tension $\varepsilon_z = \frac{\Delta l}{l_o}$

Alongx:compression $\varepsilon_x = \frac{\Delta d}{d_o}$

Isotropicx andy: $\varepsilon_y = \varepsilon_x$

[redacted]

Relationbetweenelasticandshearmoduli:$E=2G(1+\nu)$

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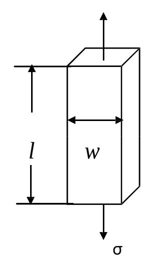
PoissonRatio

- *PoissonRatio**hasarange* $-1 \leq \nu \leq 1/2$



Lookatextremes $\Delta w/w=\Delta l/l$

- Nochangeinaspectratio: $\nu = -\frac{\Delta w/w}{\Delta l/l} = -1$

- Volume(V=AL)remainsconstant:$\Delta V=0$or$l\Delta A=-A\Delta l$

Hence,$\Delta V=(l\Delta A+A\Delta l)=0$.

Intermsofwidth,$A=w^2$,

and$\Delta A=w^2-(w+\Delta w)^2=2w\Delta w+\Delta w^2$

then

$\Delta A/A=2\Delta w/w+\Delta w^2/w^2$

inthelimit ofsmallchanges,

$\Delta A/A=2\Delta w/w$

then

$2\Delta w/w=-\Delta l/l$

$\nu = -\frac{\Delta w/w}{\Delta l/l} = -\frac{(-\frac{1}{2}\Delta l/l)}{\Delta l/l} = 1/2$

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PoissonRatio:materialsspecific

Metals:Ir	W	Ni	Cu	Al	Ag	Au	
	0.26	0.29	0.31	0.34	0.34	0.38	0.42
						genericvalue~ 1/3	

SolidArgon:0.25

CovalentSolids:	Si	Ge	Al_2O_3	TiC	
	0.27	0.28	0.23	0.19	genericvalue~ 1/4

IonicSolids: MgO 0.19

SilicaGlass:0.20

Polymers: Network(Bakelite)0.49 Chain(PE)0.40

Elastomer: HardRubber(Ebonite)0.39 (Natural)0.49

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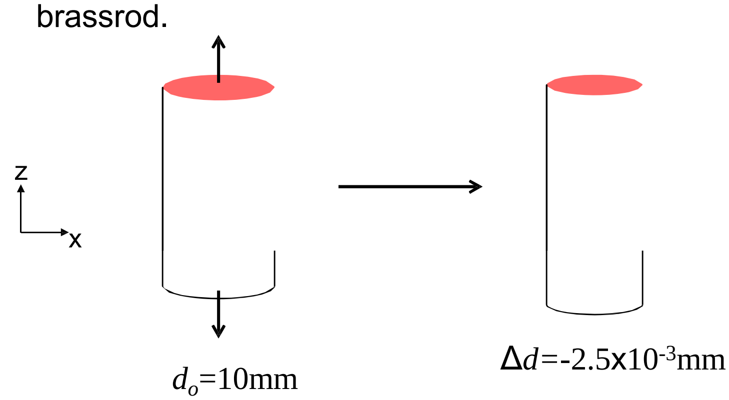
PoissonRatio:Exampleproblem

Calculatethe force necessary to producechange of-2.5x 10^{-3}mmindiameter ofa10mm diameter brassrod.



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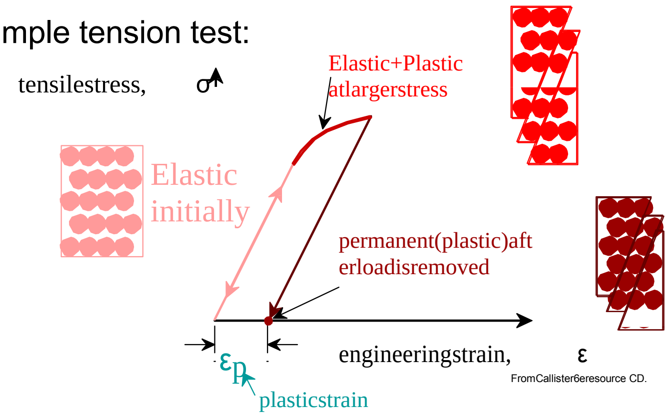
PlasticDeformation

- Simple tension test:



•Apermanentdeformation(usuallyconsideredforT<T_m/3).
•Atomsbreakbondsandformnewones.
•Inmetals,plasticdeformationoccurstypicallyatstrain≥0.005.

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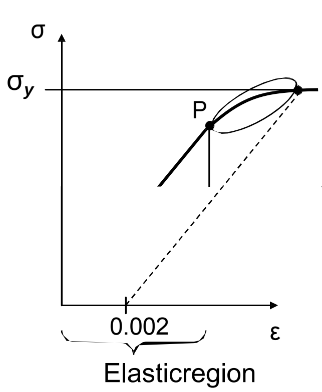
Tensileproperties

A. <u>Yieldstrength</u>(σ_y): thestrengthrequiredtoproduce averyslightyetspecifiedamount ofplasticdeformation.

Whatis thespecifiedamountofstrain?

Strainoffsetmethod

1. Startat0.002strain(formostmetals).
2. Drawaline paralleltothelinearregion.
3. σ_y=wherethedottedlinecrosses thestress-straincurve.



P=proportionallimit (beginningof deviationfromlinearbehavior.

Mixedelastic-plasticbehavior

Formaterialswith<u>nonlinear</u>elasticregion:
$\sigma_y$isdefinedasstressrequiredtoproduce specificamountofstrain(e.g.~0.005for mostmetals).

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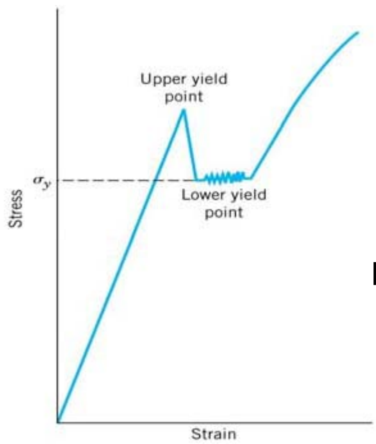
Tensileproperties

Yieldpointphenomenonoccurs when elastic-plastic transition is well-definedand abrupt.



Nooffsetmethodsrequired here.

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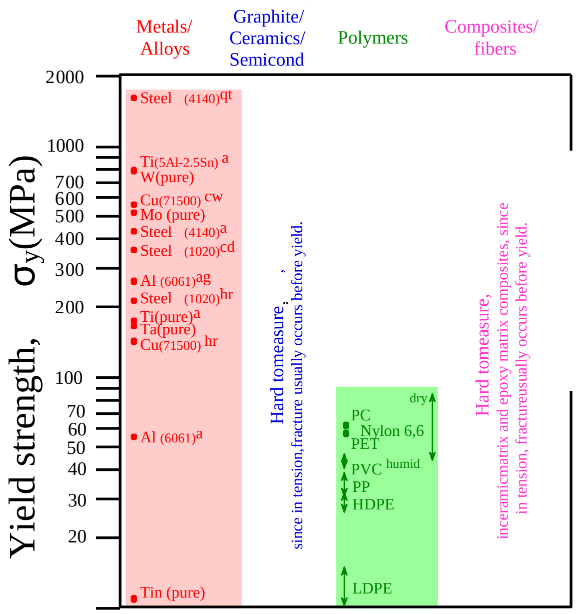
Yieldstrengthsofdifferentmaterials



$\sigma_{y(ceramics)}$ $>>\sigma_{y(metals)}$ $>>\sigma_{y(polymers)}$

RoomTvalues

BasedondatainTableB4, *Callister6e*.
a = annealedhr=hot rolledag=aged cd=colddrawncw =coldworked qt=quenched&tempered

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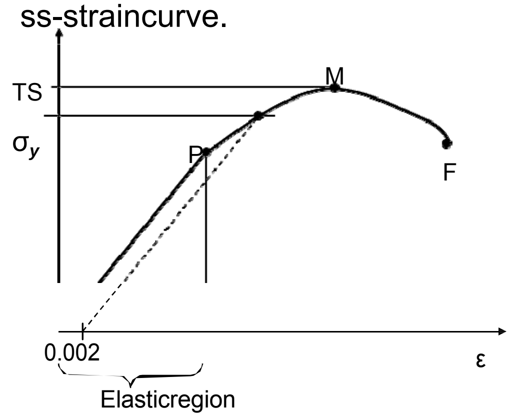
TensileProperties

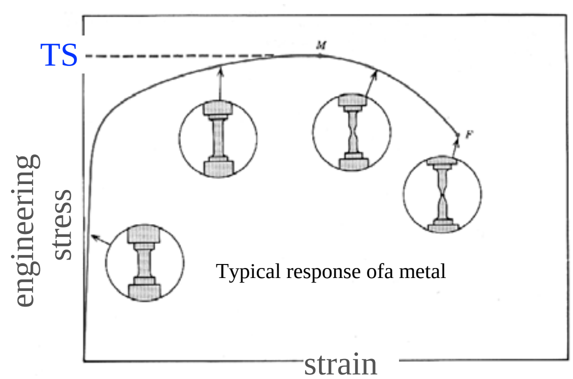
B. <u>TensileStrength</u>(TS):stressatthemaximumofstress-straincurve.



P=proportionallimit
σ_y= yieldstrength
TS=tensile strength
M=max.stressF=
fracturepoint

Note:Formostengineeringmaterials,strengthshouldbe specifiedby **<u>yield strength</u>**(*not*tensilestrength).Why? 25

Necking



AdaptedfromFig.6.11, *Callister6e.*

Necking:atmaximumstress,a small constriction (aneck) appears.
Subsequent deformation is confinedto this neck.

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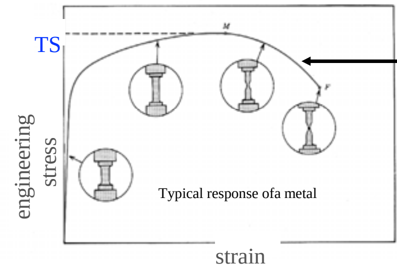
Truestressandstrain



Noticethatpastmaximumstress point,σdecreases.

Doesthismeanthatthe materialisbecomingweaker?

Neckingleadstosmallercross sectionalarea!

Recall:EngineeringStress=$\sigma = \frac{F}{A_o}$ ← Originalcrosssectionalarea!

TrueStress= $\sigma_T = \frac{F}{A_i}$

TrueStrain= $\varepsilon_T = \ln\frac{l_i}{l_o}$

A_i=instantaneousarea

l_i=instantaneouslength

Ifno net volumechange(i.e.$A_i l_i = A_o l_o$)

$\sigma_T = \sigma(1+\varepsilon)$

$\varepsilon_T = \ln(1+\varepsilon)$

Onlytrueattheonsetof necking

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Exampleproblem

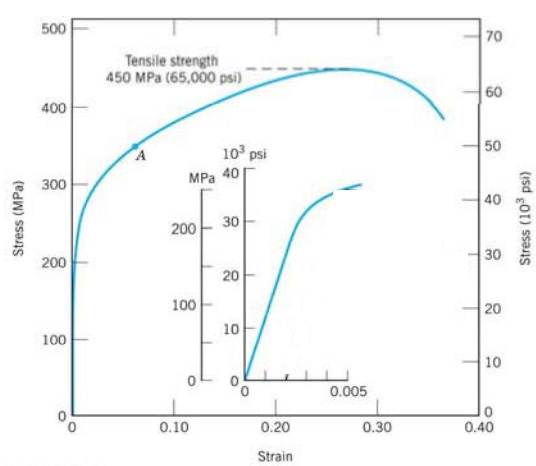

FIGURE 6.12 The stress–strain behavior for the brass specimen discussed in Example Problem 6.3.

Calculate/determinethe followingforabrass specimenthatexhibits stress-strainbehavior shownontheleft.

1) Modulusofelasticity.
2) Yieldstrength.
3) Maximumloadfora cylindricalspecimen withd=12.8mm.
4) Changeinlengthat 345MPaif theinitial lengthis250mm.

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Tensileproperties

C. <u>Ductility</u>:measureofdegreeofplasticdeformationthat hasbeensustained atfracture.

- **Ductilematerials**canundergosignificantplastic deformationbeforefracture.
- **Brittlematerials** can tolerate only very small plastic deformation.

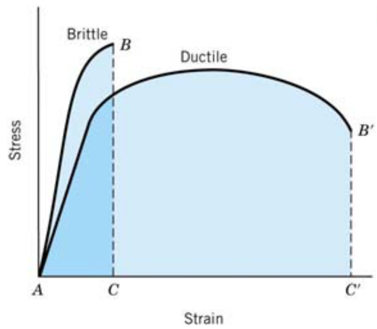

FIGURE 6.13 Schematic representations of tensile stress–strain behavior for brittle and ductile materials loaded to fracture.

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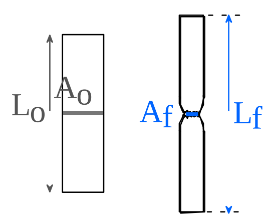
Measureofductility

$$\%\text{elongation} = \frac{l_f - l_o}{l_o} \times 100\%$$

$$\%\text{reduction in area} = \frac{A_o - A_f}{A_o} \times 100\%$$



$A_o$and$l_o$areinitial.A_f and$l_f$areat fracture.

- Note:%AR and%ELareoftencomparable.
  --Reason:crystalslipdoesnotchangematerialvolume.
  --%AR>%ELpossibleifinternalvoidsforminneck.

Typically,materialsareconsidered:brittleif%EL<5%
ductileif %EL>5%

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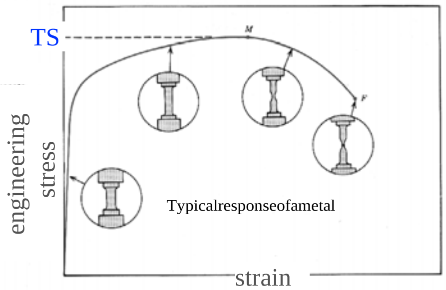
ExampleProblem: ductility& true stress

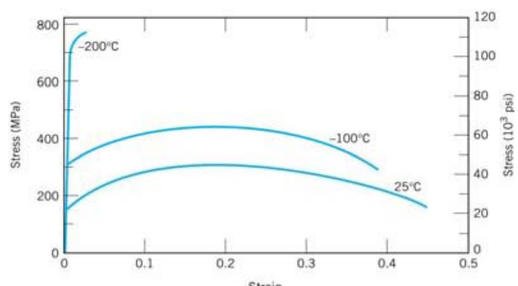


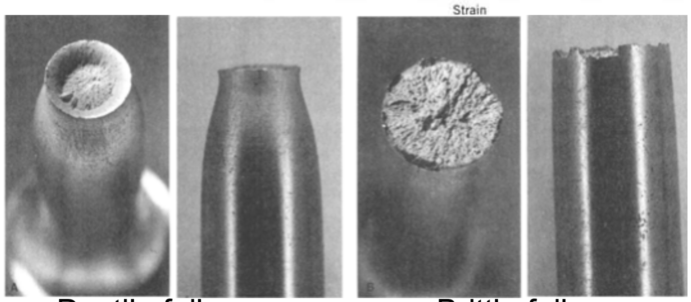
Steel specimenwith
d_o=12.8mm
Fractureatσ_f=460MPa
Crosssectionaldiameter at fracture=10.7mm

A) Calculate ductilityin termsof percentreductioninarea.
B) Thetruestressatfracture.

Note:mostmetalsareductileatRT,butcanbecome brittleatlowT

FIGURE 6.14 Engineering stress–strain behavior for iron at three temperatures.





Ductile failure Brittle failure

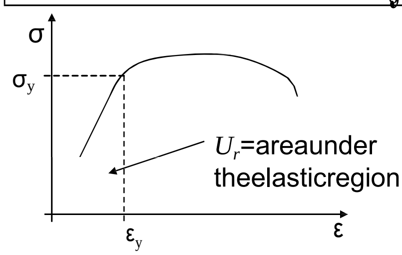
Tensile properties

D. Resilience: the capacity to absorb energy when deformed elastically and to have the absorbed energy recovered upon unloading.

Modulus of Resilience $= U_r = \int_0^{\varepsilon_y} \sigma \, d\varepsilon$

If the elastic region is perfectly linear (i.e. E is independent of ε):

$$U_r = \frac{\sigma_y^2}{2E}$$



Resilient materials have large yield strength and small elastic modulus.

E. Toughness: the ability of a material to absorb energy up to its fracture point.

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Elastic recovery after plastic deformation

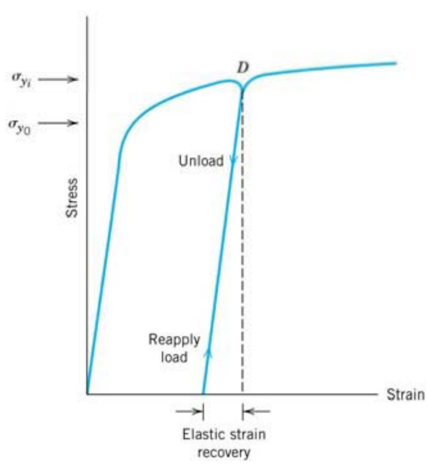

FIGURE 6.17 Schematic tensile stress–strain diagram showing the phenomena of elastic strain recovery and strain hardening. The initial yield strength is designated as σ_{y_0}; σ_{y_i} is the yield strength after releasing the load at point D, and then upon reloading.

This behavior is exploited to increase yield strengths of metals: **strain hardening** (also called **cold working**).

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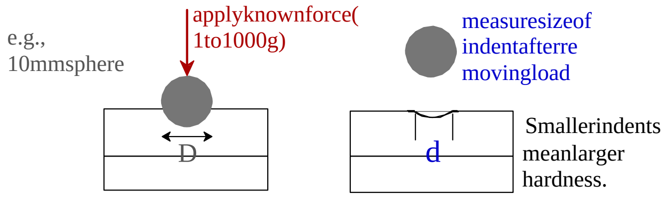
Hardness

- Resistance topermanently indentingthe surface.
- Large hardness means:
  --resistanceto plasticdeformation or crackingin compression.
  --betterwear properties.



Indentation willdependnot only onthe materialbeing testedbutalsoindentercompositionandgeometry.

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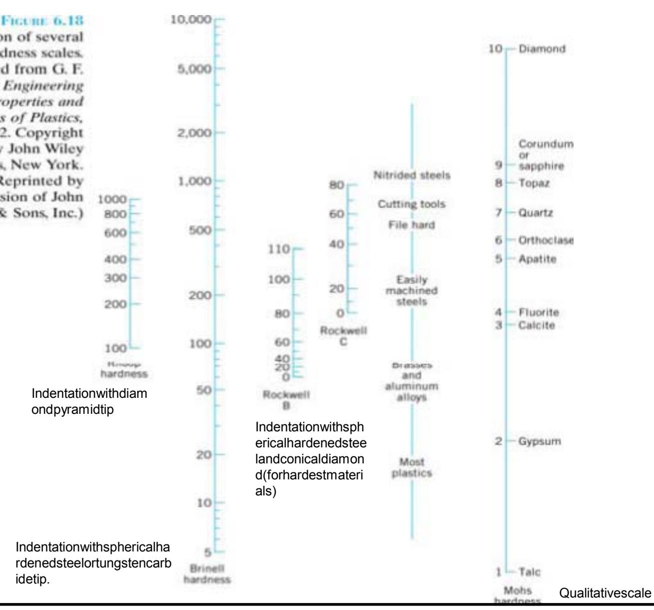
Hardnessscales

FIGURE 6.18 Comparison of several hardness scales. (Adapted from G. F. Kinney, *Engineering Properties and Applications of Plastics*, p. 202. Copyright © 1957 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)



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Correlationbetweenhardnessandtensilestrength

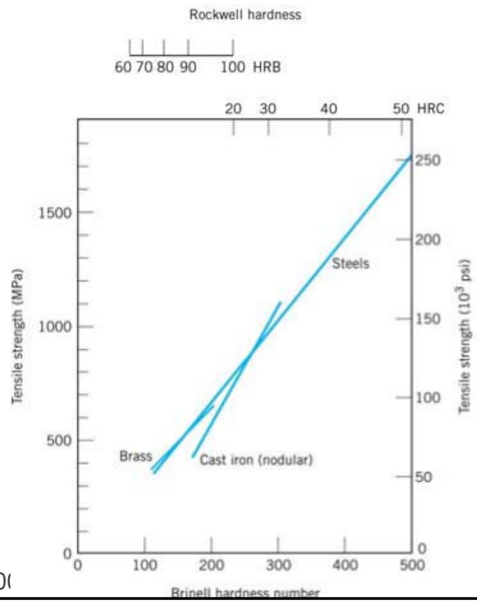

FIGURE 6.19 Relationships between hardness and tensile strength for steel, brass, and cast iron. [Data taken from *Metals Handbook: Properties and Selection: Irons and Steels*, Vol. 1, 9th edition, B. Bardes (Editor), American Society for Metals, 1978, pp. 36 and 461; and *Metals Handbook: Properties and Selection: Nonferrous Alloys and Pure Metals*, Vol. 2, 9th edition, H. Baker (Managing Editor), American Society for Metals, 1979, p. 327.]

Both**tensilestrength**and **hardness**indicatea material'sresistanceto plasticdeformation. ∴thesetwopropertiesare roughlyproportional. 37

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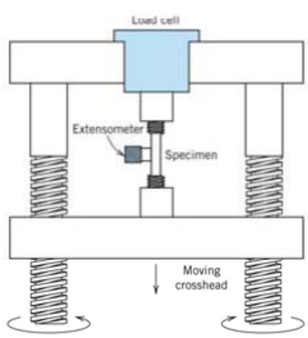
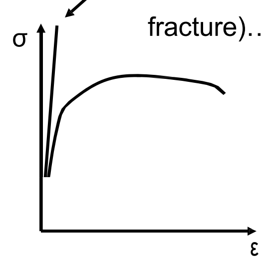
Mechanicalproperties-Ceramics

Recalltensiletestsforstress-strainbehavior…



Mostceramics(brittle): needtoapplylargestress (butvery little straintill fracture)…



Mostmetals:can getelastic modulus,yield strength,tensile strengthetc…

Infact,if thetestingapparatusis mainly madeof metal,howdowe testforceramicswithlargerfracturestrength?

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3-point bend test

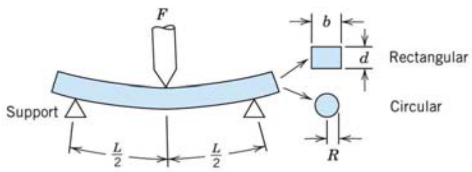
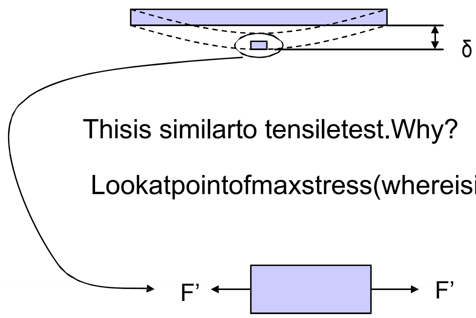


FIGURE 12.29 A three-point loading scheme for measuring the stress–strain behavior and flexural strength of brittle ceramics, including expressions for computing stress for rectangular and circular cross sections.

σ = stress = $\frac{Mc}{I}$

where M = maximum bending moment
c = distance from center of specimen to outer fibers
I = moment of inertia of cross section
F = applied load

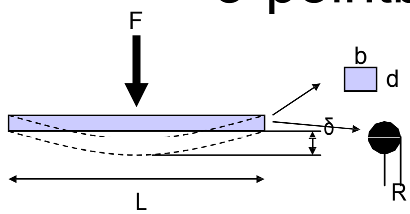
	M	c	I	σ
Rectangular	$\frac{FL}{4}$	$\frac{d}{2}$	$\frac{bd^3}{12}$	$\frac{3FL}{2bd^2}$
Circular	$\frac{FL}{4}$	R	$\frac{\pi R^4}{4}$	$\frac{FL}{\pi R^3}$



This is similar to tensile test. Why?

Look at point of max stress (where is it?).

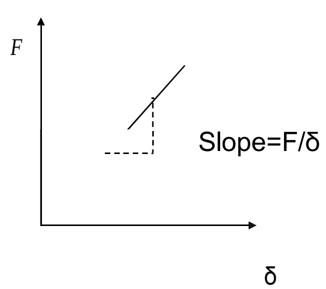
3-point bend test



Elastic modulus is proportional to F/δ

$$E_{rect.} = \frac{F}{\delta}\left(\frac{L^3}{4bd^3}\right)$$

$$E_{circ.} = \frac{F}{\delta}\left(\frac{L^3}{4\pi R^4}\right)$$



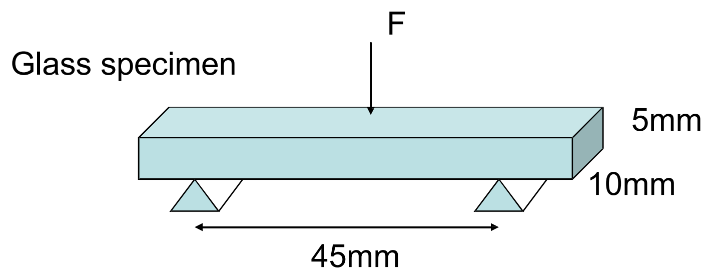
Flexural strength: strength at fracture

$$\sigma_{fs} = 2\frac{3F_fL}{4bd^2}$$ Rectangular

$$\sigma_{fs} = \frac{F_fL}{\pi R^3}$$ Circular

F_f = force at fracture

Example1:3ptbend test



a) Calculateflexuralstrengthifthe loadatfractureis 290N.

b) Calculatethemaximumdeflection atF=266N

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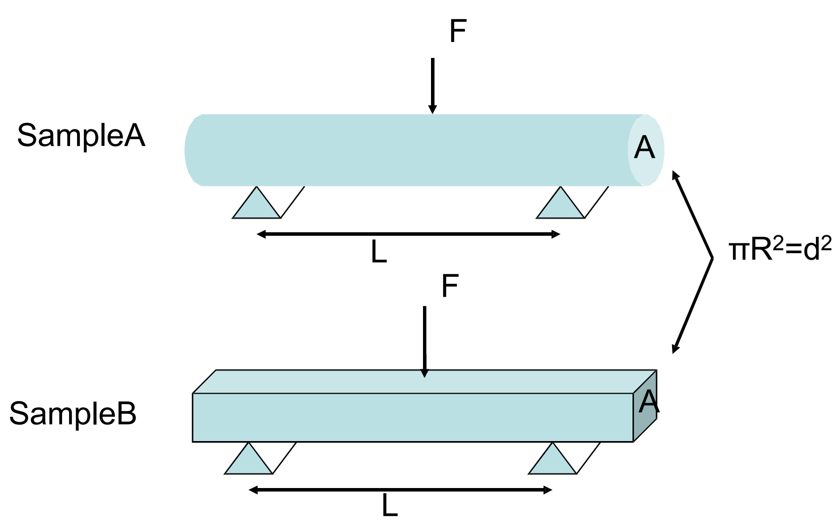
Example2:3ptbend test



Comparethe ratioof flexuralstrengths

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Polymerstress-strainbehavior

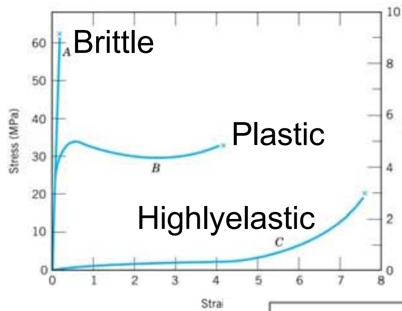

FIGURE 15.1 The stress–strain behavior for brittle (curve *A*), plastic (curve *B*), and highly elastic (elastomeric) (curve *C*) polymers.

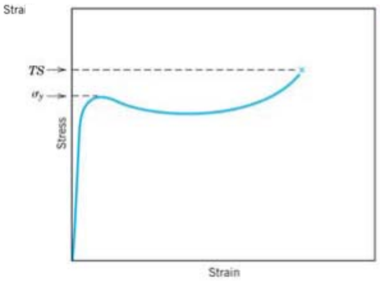

FIGURE 15.2 Schematic stress–strain curve for a plastic polymer showing how yield and tensile strengths are determined.

Plastic polymers

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Polymerstress-strainbehavior

- Modulusofelasticity~7MPato4GPa.
- Tensilestrengthupto~100MPa.
- Plasticelongationcanbe>100%.
- TypicallyhighlyTsensitivemechanicalproperties.

Table 15.1 Room-Temperature Mechanical Characteristics of Some of the More Common Polymers

Material	*Specific Gravity*	*Tensile Modulus [GPa (ksi)]*	*Tensile Strength [MPa (ksi)]*	*Yield Strength [MPa (ksi)]*	*Elongation at Break (%)*
Polyethylene (low density)	0.917–0.932	0.17–0.28 (25–41)	8.3–31.4 (1.2–4.55)	9.0–14.5 (1.3–2.1)	100–650
Polyethylene (high density)	0.952–0.965	1.06–1.09 (155–158)	22.1–31.0 (3.2–4.5)	26.2–33.1 (3.8–4.8)	10–1200
Polyvinyl chloride	1.30–1.58	2.4–4.1 (350–600)	40.7–51.7 (5.9–7.5)	40.7–44.8 (5.9–6.5)	40–80
Polytetrafluoroethylene	2.14–2.20	0.40–0.55 (58–80)	20.7–34.5 (3.0–5.0)	—	200–400
Polypropylene	0.90–0.91	1.14–1.55 (165–225)	31–41.4 (4.5–6.0)	31.0–37.2 (4.5–5.4)	100–600
Polystyrene	1.04–1.05	2.28–3.28 (330–475)	35.9–51.7 (5.2–7.5)	—	1.2–2.5
Polymethyl methacrylate	1.17–1.20	2.24–3.24 (325–470)	48.3–72.4 (7.0–10.5)	53.8–73.1 (7.8–10.6)	2.0–5.5
Phenol-formaldehyde	1.24–1.32	2.76–4.83 (400–700)	34.5–62.1 (5.0–9.0)	—	1.5–2.0
Nylon 6,6	1.13–1.15	1.58–3.80 (230–550)	75.9–94.5 (11.0–13.7)	44.8–82.8 (6.5–12)	15–300
Polyester (PET)	1.29–1.40	2.8–4.1	48.3–72.4	59.3	30–300

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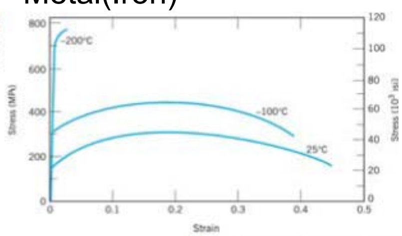
Polymerstress-strainbehavior

Metal(Iron)

Figure 6.14 Engineering stress–strain behavior for iron at three temperatures.



Polymer (PMMA)

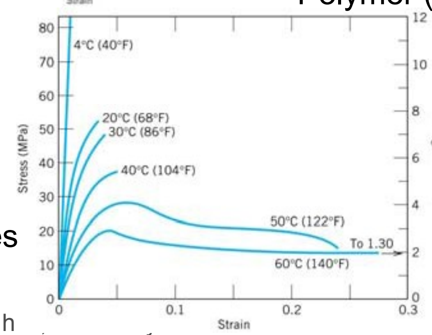
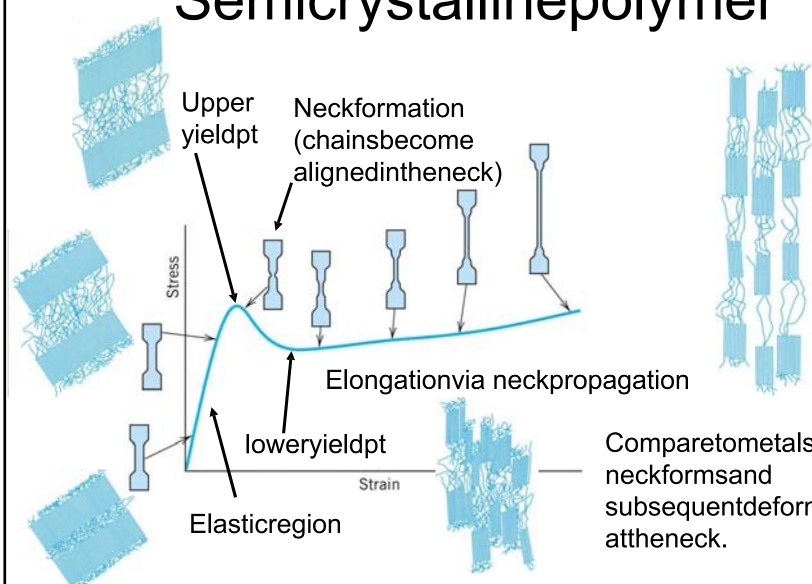


Figure 15.3 The influence of temperature on the stress–strain characteristics of polymethyl methacrylate. (From T. S. Carswell and H. K. Nason, "Effect of Environmental Conditions on the Mechanical Properties of Organic Plastics," *Symposium on Plastics*, American Society for Testing and Materials, Philadelphia, 1944. Copyright, ASTM, 1916 Race Street, Philadelphia, PA 19103. Reprinted with permission.)

AsTincreases:
- Edecreases
- TSdecreases
- Ductilityincreases

h 0

Semicrystallinepolymer



Comparetometalswhere neckformsand subsequentdeformationis atthenecK.

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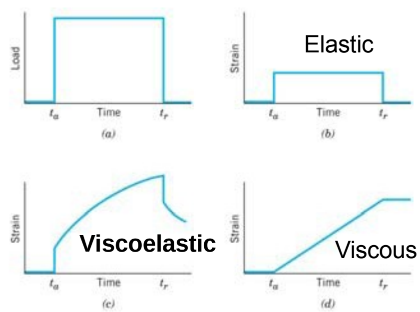
Viscoelasticdeformation

Amorphouspolymersmayactlike:

- GlassatlowT($T<T_g$Glasstransitiontemperature).
- Rubberysolid ($T_m>T>T_g$).
- Viscousliquid($T>T_m$).

Viscoelasticity:mechanicalcharacteristicsexhibitingbothviscous flowandelasticdeformation(rubberysolid).

FIGURE 15.5 (*a*) Load versus time, where load is applied instantaneously at time t_a and released at t_r. For the load–time cycle in (*a*), the strain-versus-time responses are for totally elastic (*b*), viscoelastic (*c*), and viscous (*d*) behavior.



Instantaneous responsew/ complete recovery.

Delayed response. Notreversible.

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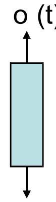
Viscoelasticrelaxationmodulus

RecallElasticModulus: $\sigma = E\varepsilon$

Themoduluscanbeboth**time**and**temperature**dependent.

σ (t)



σ (t)

1. AtaconstantT,applysmallstress(σ)to achieveinitialstrain(ε_o).
2. Adjustσtomaintainε_o.
3. RepeatatdifferentT.

ForeachT:**RelaxationModulus**

$$E_r(t) = \frac{\sigma(t)}{\varepsilon_o}$$

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Viscoelasticrelaxationmodulus

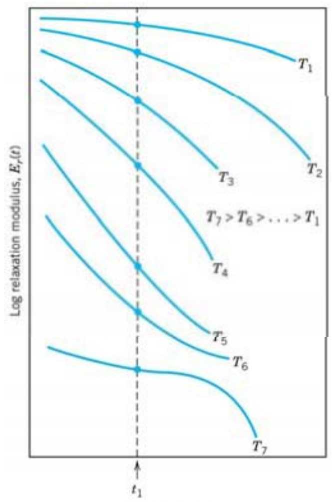

Fig.15.6Callister

Plotasa function ofTata fixedt.

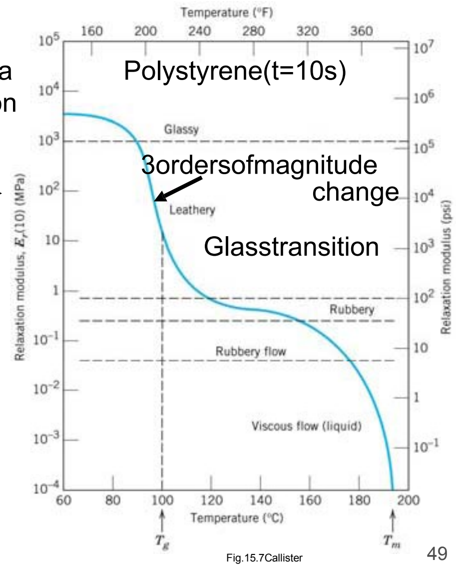

Fig.15.7Callister

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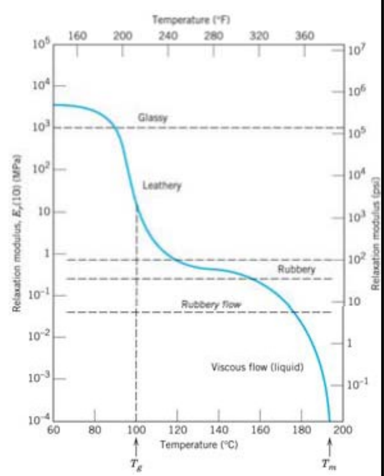
Viscoelasticrelaxationmodulus

- **Glassyregion:**
  - Initially independent ofT.
  - Rigid&brittle (molecular chains “frozen”in place).
- **Glasstransitionregion:**
  - Time-dependent deformation.
  - Incompleterecovery uponrelease ofload.
- **Rubbery region:**
  - Bothviscousand elastic.
  - Low relaxationmodulus -> easy todeform.
- **Viscous flowregion:**
  - High viscosity liquid.
  - Completelyviscousdeformation.



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Viscoelasticrelaxationmodulus

Molecularstructureeffect

Polystyrene

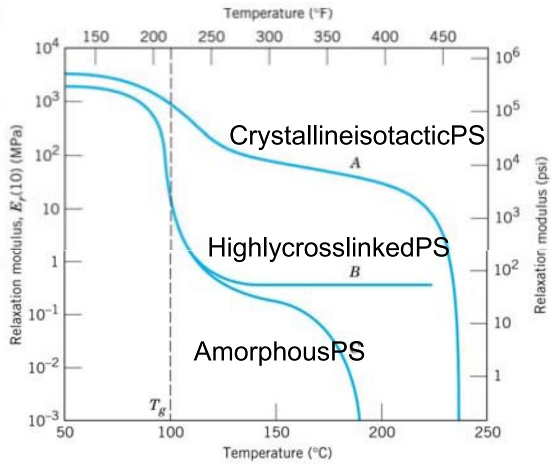

FIGURE 15.8 Logarithm of the relaxation modulus versus temperature for crystalline isotactic (curve *A*), lightly crosslinked atactic (curve *B*), and amorphous (curve *C*) polystyrene. (From A. V. Tobolsky, *Properties and Structures of Polymers.* Copyright © 1960 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

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Viscoelasticcreep

Timedependentdeformation whenstressis kept constant(as opposedtoconstantstrainfor viscoelastic relaxation).

Creep modulus:

$$E_c(t) = \frac{\sigma_o}{\varepsilon(t)}$$

Similar to relaxationmodulus, creepmodulusis dependentonTandstructure.

Ingeneral: $E_c(t)$decreases with increasingT

$E_c(t)$increaseswith increasingcrystallinity.

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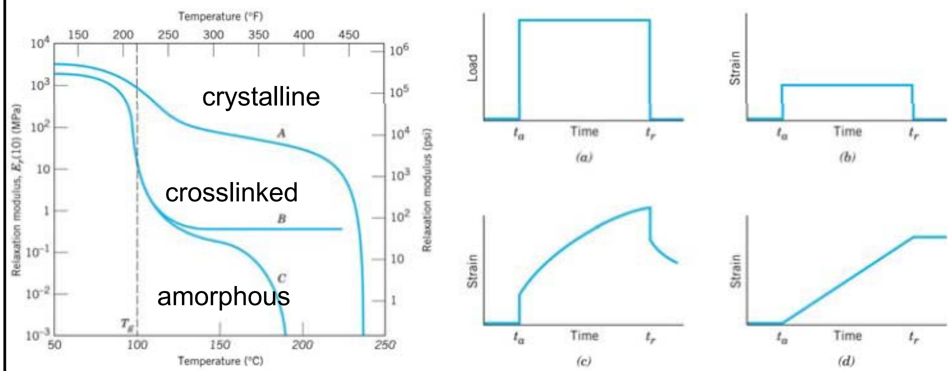
Exampleproblem



Whichbehaviorwill polystyreneexhibit if itis:

1) amorphousanddeformedat120°C?
2) amorphousanddeformedat180°C?
3) crystallineanddeformedat70°C?
4) crosslinkedanddeformedat180°C?

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Conceptsto remember

- Tensile, compressive, shear,and torsionalstress.Strain.
- Elastic vs.Plastic deformation.
- Modulusofelasticity.
- Yield and tensilestrengths.
- Poisson ratio.
- Truevs.Engineeringstressandstrain.
- Necking.
- Ductility,Resilience,Toughness,Hardness.
- Polymerstress-strainbehavior.
- Viscoelasticrelaxation andcreep.

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