Design of Machine Elements

by

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Lectures 7-13

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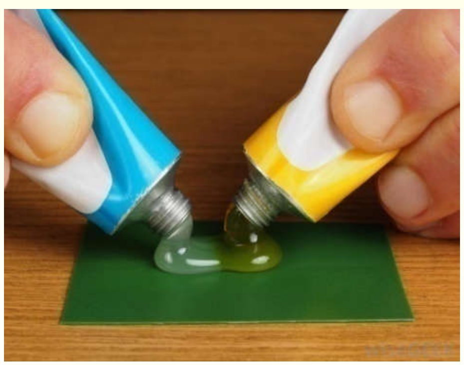
Engineering Materials: Broad Classification

Polymers

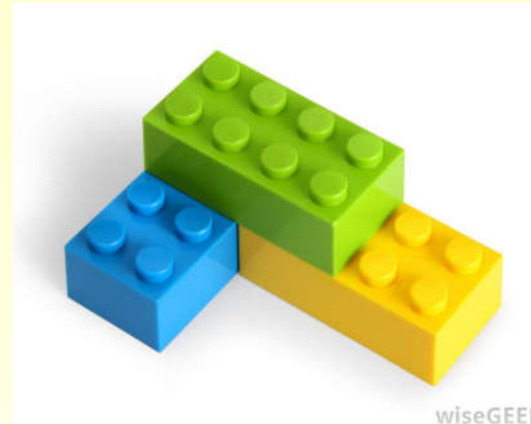
Metals

Ceramics

Polymers: Bonding based classification



Thermosets



Thermoplastics

Polymers: Mechanical Behavior Based Characterization

Vulcanized rubber

SBS (thermoplastic) rubber

Silicone

Polyurethane (thermoplastic)

Nitrile/Butyl rubber

Elastomers

Polymers: Mechanical Behavior Based Characterization

PMMA (Acrylic) glass (Used for their higher scratch resistance and transparency)

Polycarbonate (Relatively expensive, used for their higher impact resistance and transparency)

Plastics: Hard and Stiff

Polymers: Mechanical Behavior Based Characterization

Polyethylene Terephthalate (PET)

Polystyrene (hard but brittle)

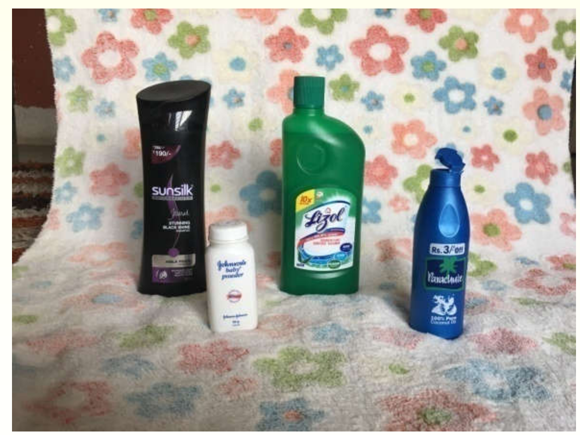
Polypropylene (most widely used plastic in consumer products

Plastics: Hard and Stiff

Polymers: Mechanical Behavior Based Characterization

Acrylonitrile butadiene styrene (ABS), Hard and tough, degrades with exposure to sun right

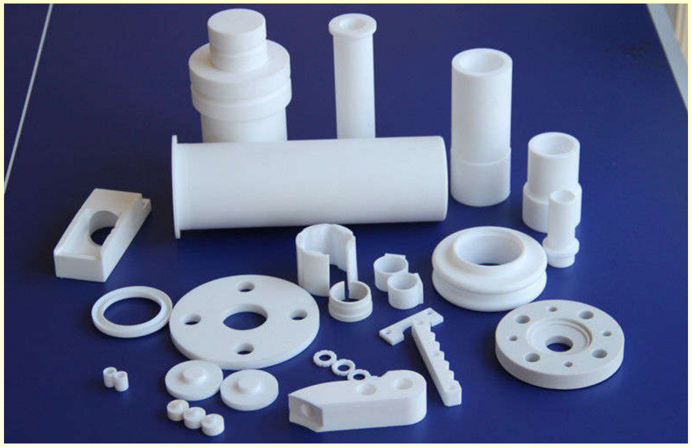
LDPE (Compliant, tough)



HDPE (Offers good solvent resistance, tough)

Plastics: Hard and Stiff

Polymers: Mechanical Behavior Based Characterization



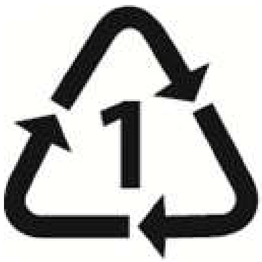
Polytetrafluoroethylene (Teflon, Popular for providing low friction coefficient)

Melamine

Nylon (Expensive, stiff, tough, wear resistant)

Plastics: Hard and Stiff

What do Recycling Symbols on Plastics Mean?

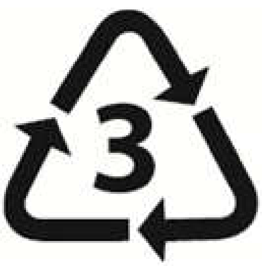


PET, PETE
(Polyethylene Terephthalate)

- Soft drink, water and salad dressing bottles; peanut butter and jam jars…
- Suitable to store cold or warm drinks. Bad idea for hot drinks.

HDPE
(High-density Polyethylene)

- Water pipes, milk, juice and water bottles; grocery bags, some shampoo / toiletry bottles…



PVC
(Polyvinyl Chloride)

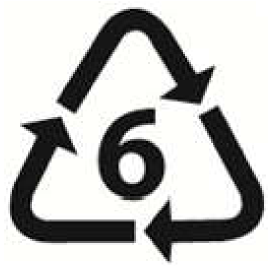
- Not used for food packaging.
- Pipes, cables, furniture, clothes, toys…

LDPE
(Low-density Polyethylene)

- Frozen food bags; squeezable bottles, e.g. honey, mustard; cling films; flexible container lids….

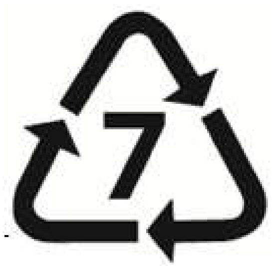
PP
(Polypropylene)

- Reusable microwaveable ware; kitchenware; yogurt containers; microwaveable disposable take-away containers; disposable cups; plates….



PS
(Polystyrene)

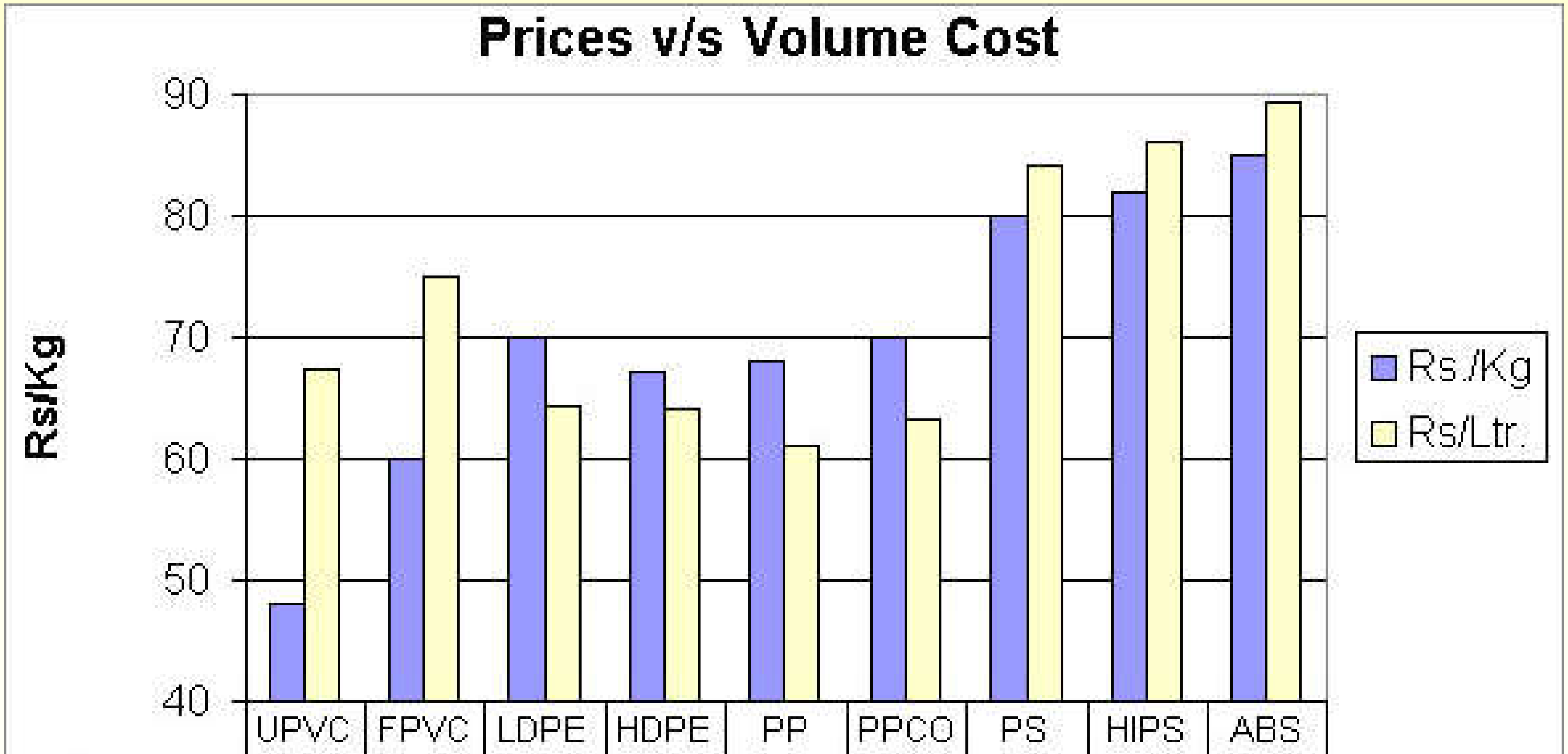
- Egg cartons; packing peanuts; disposable cups, plates, trays and cutlery; disposable take-away containers;…
Avoid for food storage!



Other
(often polycarbonate or ABS)

- Beverage bottles; baby milk bottles. compact discs; "unbreakable" glazing; lenses including sunglasses, prescription glasses, automotive headlamps, riot shields, instrument panels…

Price of a few commonly used plastics



	UPVC	FPVC	LDPE	HDPE	PP	PPCO	PS	HIPS	ABS
Rs./Kg	48	60	70	67	68	70	80	82	85
Rs/Ltr.	67.2	75	64.4	64.32	61.2	63.35	84	86.1	89.25

Metals: Popular ones

Steels

- Cost ~ Rs 50 Rs/kg
- Density 7.8 g/cc
- E = 200 GPa
- UTS = 300 MPa to 1750 MPa
- Thermal conductivity = 15 to 50 W/mK
- Electrical resistivity ~ 100 n Ohm/m
- Melting point = 1440 degrees C
- Annual usage in India ~ 60 million tonnes
- Iron electrochemical potential: -0.44

Aluminum

- Cost ~ Rs 240 Rs/kg
- Density 2.7 g/cc
- E = 70 GPa
- UTS = 80 MPa to 550 MPa
- Thermal conductivity = 237 W/mK
- Electrical resistivity ~ 30 n Ohm/m
- Melting point = 660 degrees C
- Annual usage in India ~ 1 million tonnes

Metals: Popular ones

Copper

- Cost ~ Rs 500 Rs/kg
- Density 8.96 g/cc
- E = 115 GPa
- Yield stress = 30 MPa to 550 MPa
- Thermal conductivity = 401 W/mK
- Electrical resistivity ~ 17 n Ohm/m
- Melting point = 1080 degrees C
- Annual usage in India ~ 0.7 million tonnes

Zinc

- Cost ~ Rs 300 Rs/kg
- Density 7.14 g/cc
- E = 108 GPa
- UTS = 100-150 MPa
- Thermal conductivity = 160 W/mK
- Electrical resistivity ~ 60 n Ohm/m
- Melting point = 420 degrees C
- Annual usage in India ~ 0.5 million tonnes
- Electrochemical potential: -0.76

Metals: Popular ones

Tin

- Cost ~ Rs 60 Rs/kg
- Density 7.2 g/cc
- E = 50 GPa
- UTS = 20 MPa
- Thermal conductivity = 67 W/m
- Electrical resistivity ~ 115 n Ohm/m
- Melting point = 230 degrees C
- Soft, corrosion resistant metal

Titanium

- Cost ~ Rs 2000 Rs/kg
- Density 4.5 g/cc
- E = 115 GPa
- UTS = 250 MPa to 1300 MPa
- Thermal conductivity = 22 W/mK
- Electrical resistivity ~ 420 n Ohm/m
- Melting point = 1670 degrees C
- Excellent corrosion resistance, bio-compatible
- Ti-6Al-4V most widely used alloy0

Metals: Popular ones

Nickel

- Cost ~ Rs 600 Rs/kg
- Density 8.91 g/cc
- E = 200 GPa
- UTS = 450-1200 MPa
- Thermal conductivity = 90 W/m
- Electrical resistivity ~ 70 n Ohm/m
- Melting point = 1455 degrees C
- Ni based supper alloys have excellent high temperature strength, corrosion resistance, oxidation resistance
- Inconel (~ Rs 2000/kg) most popular alloy

Tungsten

- Cost ~ Rs 3000-5000 Rs/kg
- Density 19.2 g/cc
- E = 411 GPa
- UTS = 2000 MPa
- Thermal conductivity = 173 W/m
- Electrical resistivity ~ 50 n Ohm/m
- Melting point = 3422 degrees C
- Refractory metal. Can be used up to around 1650 degrees C with protective coatings

Metals: Popular ones

Lead

- Cost ~ Rs 150 Rs/kg
- Density 11.34 g/cc
- E = 16 GPa
- UTS = 18 MPa
- Thermal conductivity = 35 W/m
- Electrical resistivity ~ 208 n Ohm/m
- Melting point = 327 degrees C

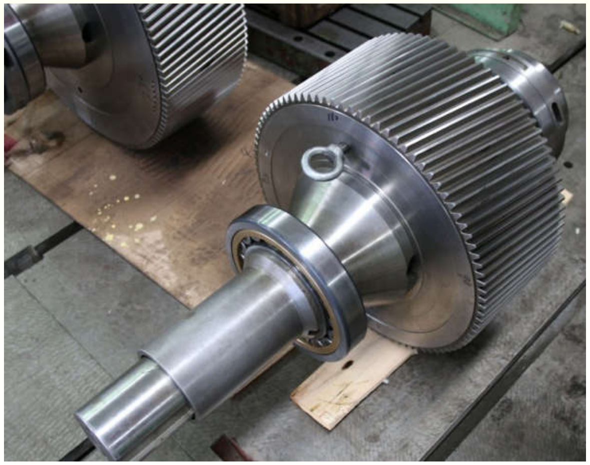
Popular Steels: AISI 4340

Chemical analysis of AISI 4340 alloy steel

Elements	C	Si	Mn	Ni	Cr	Mo	P	S
wt.(%)	0.39	0.24	0.61	1.46	0.67	0.17	0.021	0.006

Properties	Metric
Tensile strength	745 MPa
Yield strength	470 MPa
Bulk modulus (typical for steel)	140 GPa
Shear modulus (typical for steel)	80 GPa
Elastic modulus	190-210 GPa
Poisson's ratio	0.27-0.30
Elongation at break	22%

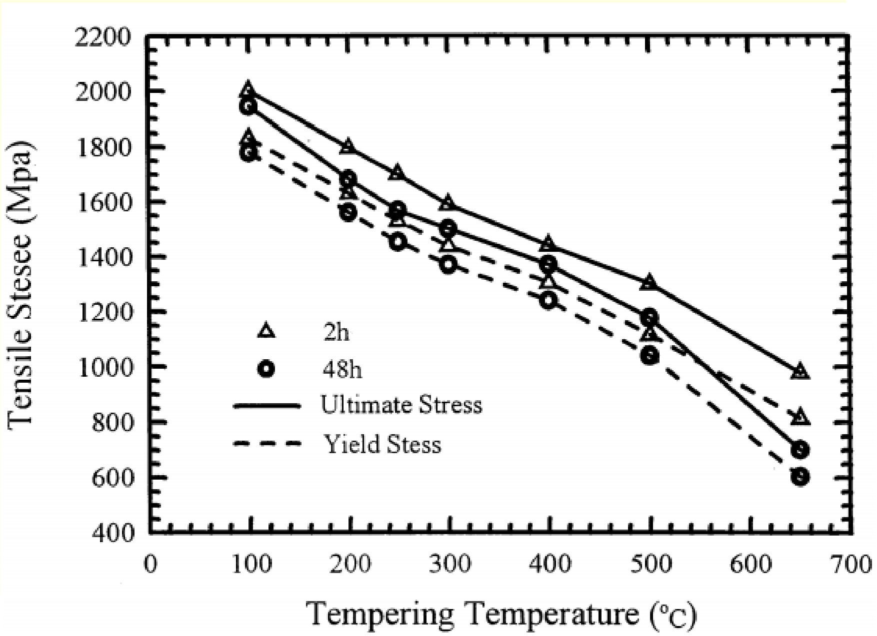
Properties in annealed condition

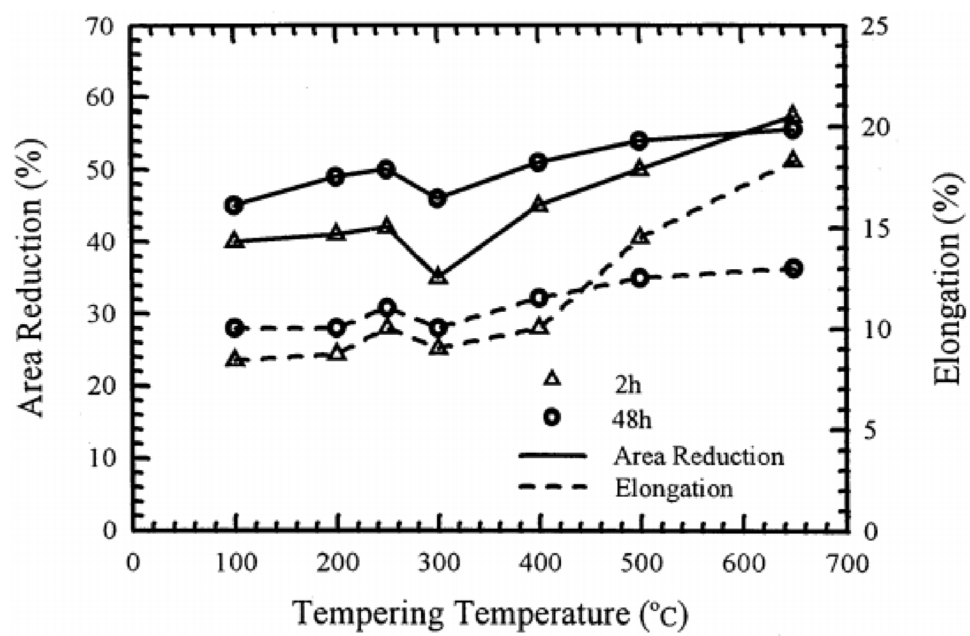


AISI 4340: Properties After Heat Treatment

The mechanical properties of AISI 4340 alloy steel after 48 h tempering

Tempering temperature (°C)	100	200	250	300	400	500	650	Quenching
σ_y (MPa)	1778	1557	1450	1367	1237	1037	600	2015
σ_T (MPa)	1940	1677	1564	1497	1366	1172	699	2214
Hv (62.5 kg)	597	512	470	457	430	379	660	660
A (%)	44	48	50	44	50	52	33.7	33.7
ε (%)	9.8	9.8	11	9.7	11.5	12.5	4.5	4.5
n	0.5	0.44	0.40	0.36	0.31	0.23	0.57	0.57



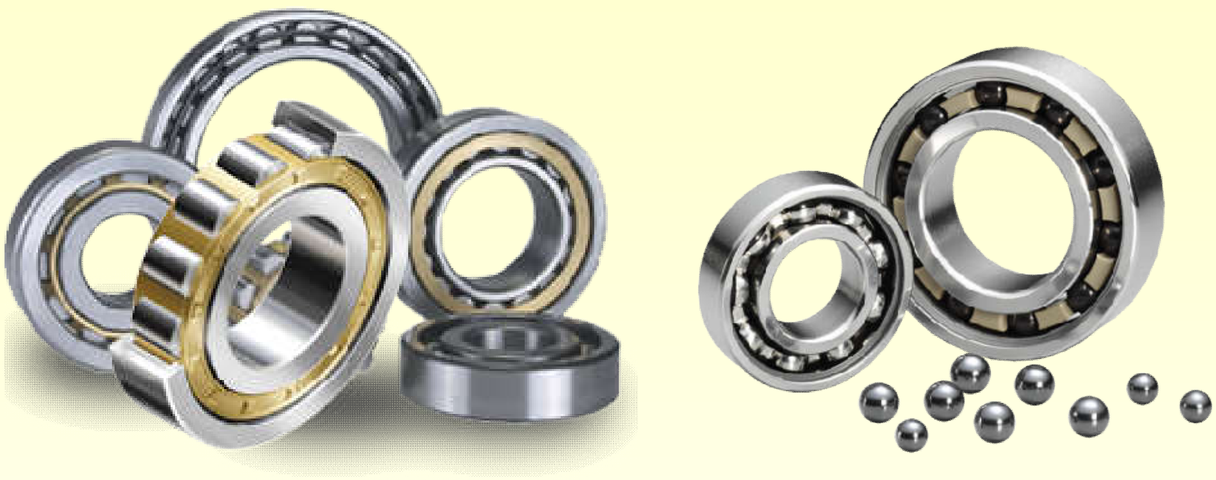


Ref: Lee and Su, 1999

Used after quenching and heat treatment wherever high hardness, wear resistance, and high toughness is desired, e.g. shafts, cams, gears, etc.

Popular Steels: AISI 52100

Element	Content (%)
Iron, Fe	96.5 - 97.32
Chromium, Cr	1.30 - 1.60
Carbon, C	0.980 - 1.10
Manganese, Mn	0.250 - 0.450
Silicon, Si	0.150 - 0.300
Sulfur, S	≤ 0.0250
Phosphorous, P	≤ 0.0250



Temperature (°C)	22	200	400	600	800	1000
Yield Strength (MPa) (0.2% offset except 22°C)	1410.17	1672.26	915.94	80.91	40.80	18.65
Tensile Strength (MPa)	NA#	2482.85	1221.36	221.46	84.06	33.14
Fracture Strength (MPa)	1866.85	2731.14	1343.50	243.61	92.47	36.45
Yield Strain (10^{-2})	0.70	1.09	1.09	0.30	0.30	0.20
Tensile Strain (10^{-2})	1.10	4.46	2.77	3.23	5.00	6.59
Fracture Strain (10^{-2})	1.10	6.97	74.35	252.18	128.37	42.64
Young's Modulus (GPa)	201.33	178.58	162.72	103.42	86.87	66.88*
Poisson's Ratio	0.277	0.269	0.255	0.342	0.396	0.490

Properties after quenching and tempering at 150 C for 1 hour.
Ref: Guo and Liu, 2002.

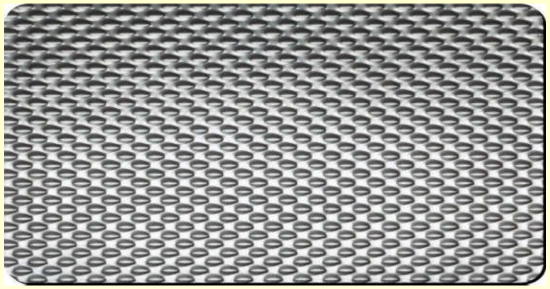
Used after quenching and heat treatment wherever high hardness and wear resistance at moderate temperatures (~200 C) is desired, e.g. for raceways and rollers in roller bearings.

Popular Steels: SS 304

MECHANICAL PROPERTIES

Typical Room Temperature Mechanical Properties

	UTS ksi (MPa)	0.2% YS ksi (MPa)	Elongation % in 2" (50.8 mm)	Hardness Rockwell
Type 304L	85 (586)	35 (241)	55	B80
Type 304	90 (621)	42 (290)	55	B82



COMPOSITION

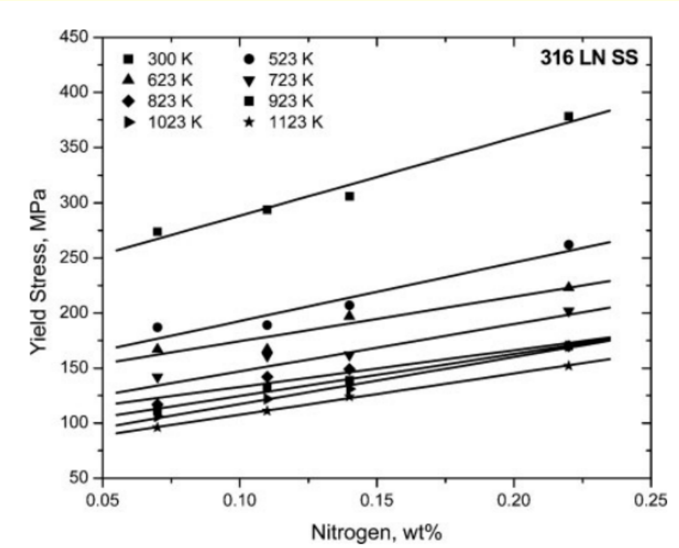
	Type 304 %	Type 304L %
Carbon	0.08 max.	0.03 max.
Manganese	2.00 max.	2.00 max.
Phosphorus	0.045 max.	0.045 max.
Sulfur	0.030 max.	0.030 max.
Silicon	0.75 max.	0.75 max.
Chromium	18.00-20.00	18.0-20.0
Nickel	8.00-12.00	8.0-12.0
Nitrogen	0.10 max.	0.10 max.
Iron	Balance	Balance

SS 304 has good corrosion resistance (expect in saline conditions or in presence of industrial solvents) and has good formability. It however work hardens easily and stress relieving is need in critical applications. It is used in structural panels, cooking utensils, expensive bathroom fitting, chemical plants, rust free wire meshes, etc.

Popular Steels: SS 316LN

Table 1 Chemical composition of 316LN SS, wt-%

Specification		N	C	Mn	Cr	Mo	Ni	Si	S	P	Fe	Grain size, µm
Heat no.	Designation	0·06–0·22	0·02–0·03	1·6 – 2·0	17–18	2·30–2·50	12·0–12·5	0·50 max.	0·01 max.	0·03 max.	Bal.	<180
H8344	7N	0·07	0·027	1·7	17·53	2·49	12·2	0·22	0·0055	0·013	Bal.	87·3 ±8·7
H8335	11N	0·11	0·033	1·78	17·62	2·51	12·27	0·21	0·0055	0·015	Bal.	95·8 ±8·0
H8334	14N	0·14	0·025	1·74	17·57	2·53	12·15	0·20	0·0041	0·017	Bal.	77·7 ±7·7
H8345	22N	0·22	0·028	1·70	17·57	2·54	12·36	0·20	0·0055	0·018	Bal.	86·8 ±10·9



Yield stress as a function of nitrogen weight percentage and working temperature in K

(a)

(b)

(c)

(d)

Applications where SS 316 is used: (a) surgical instruments, (b) Food processing/Pharmaceutical industries, (c) Medical needles, (d) Pipes where salty conditions can exist.

SS 316 has greater corrosion (pitting) resistance than SS 304, particularly against chlorides and other industrial solvents, from presence of 2-3% Mo. It also has higher high temperature strength, creep resistance, corrosion resistance, and resistance to stress corrosion cracking even at weld locations.

Ref: Ganesan, Mathew, and Sankara Rao, 2013.

Ceramics

Alumina

- Cost ~ Rs 50 Rs/kg (powder cost)
- Density ~ 4 g/cc
- E ~ 410 GPa
- Compressive strength ~ 3000 MPa
- Flexural strength ~ 350 MPa
- Tensile strength ~ 250 MPa
- Thermal conductivity ~ 30 W/mK
- Melting point = 2072 degrees C

Silicon Carbide

- Cost ~ Rs 200 Rs/kg (powder cost)
- Density ~ 3.1 g/cc
- E ~ 410 GPa
- Compressive strength ~ 4000 MPa
- Flexural strength ~ 550 MPa
- Fracture toughness ~ 4 MPa Sqrt m
- Thermal conductivity ~ 120 W/mK
- Melting point = 2730 degrees C

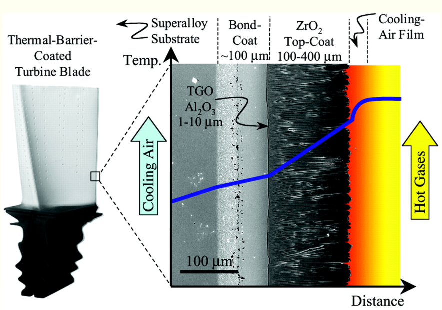
High hardness, abrasion resistance, electric insulation, corrosion resistance, heat impact resistance, bio inert capacity, high chemical resistance and high melting point are reasons for going with ceramics as opposed to metals. They are however, difficult to process (sintering is only way to make parts).

Ref: https://srdata.nist.gov/CeramicDataPortal/Pds/Scdaos

Ceramics

Tungsten carbide

- Density ~ 15.6 g/cc
- E ~ 600 GPa
- Compressive strength ~ 5100 MPa
- Fracture toughness ~ 3 MPa Sqrt m
- Thermal conductivity ~60 W/mK
- Melting point = 3100 degrees C



Cross-sectional scanning electron micrograph (SEM) of an electron-beam physical-vapor deposited (EB-PVD) TBC, superimposed onto a schematic diagram showing the temperature reduction provided by the TBC. The turbine blade contains internal hollow channels for air-cooling, whereas the outside hot-section surface is thermal barrier-coated, setting up a temperature gradient across the TBC.

(Yttria stabilized) Zirconia

- Density ~ 5.7 g/cc
- E ~ 205 GPa
- Compressive strength ~ 2000 MPa
- Flexural strength ~ 1000 MPa
- Fracture toughness ~ 10 MPa Sqrt m
- Thermal conductivity ~ 2 W/mK
- Melting point = 2715 degrees C

Ceramics

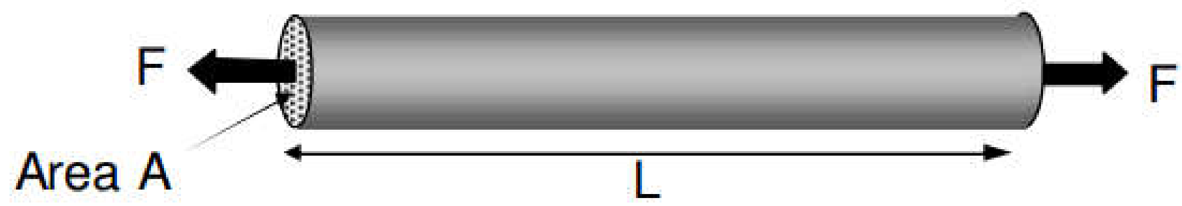
Silicon Nitride

- Density ~ 3.2 g/cc
- Thermal conductivity ~ 30 W/mK
- Melting point ~ 1900 degrees C

Materials Selection

Deriving Performance Indices: Light, stiff tie

Stiff tie of length L and minimum mass



Function — *Tie-rod*

Objective — *Minimise mass m:*

$$m = A\,L\,\rho \qquad (1)$$

Constraints — *Stiffness* of the tie S:

$$S = \frac{E\,A}{L} \qquad (2)$$

m = mass
A = area
L = length
ρ = density
S = stiffness
E = Youngs Modulus

Free variables

- *Material choice*
- *Section area A; eliminate in (1) using (2):*

$$m = S L^2 \left(\frac{\rho}{E}\right)$$

Chose materials with smallest $\left(\frac{\rho}{E}\right)$

Ref: www.diim.unict.it/users/fgiudice/pdfs/SM_2.3.pdf

Deriving Performance Indices: Light, stiff beam

Function *Beam* (solid square section).

Objective *Minimise mass*, m, where:

$$m = AL\rho = b^2 L\rho$$

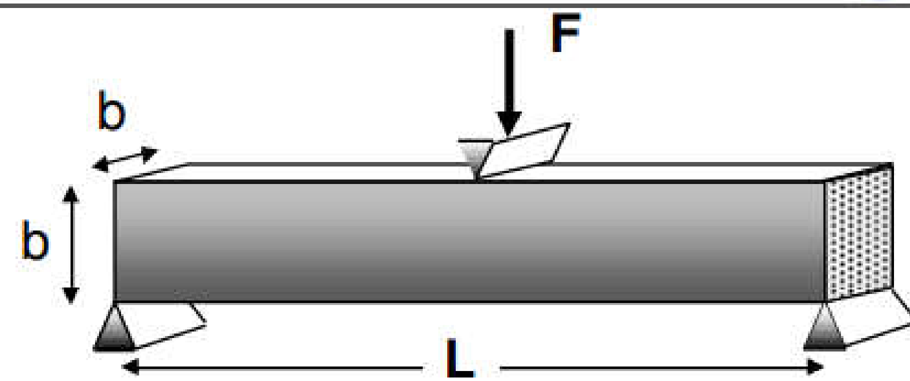
Constraint *Stiffness* of the beam S:

$$S = \frac{CEI}{L^3}$$

ρ

I is the second moment of area:

$$I = \frac{b^4}{12}$$



m = mass
A = area
L = length
ρ = density
b = edge length
S = stiffness
I = second moment of area
E = Youngs Modulus

Free variables
- *Material choice.*
- *Edge length b.* Combining the equations gives:

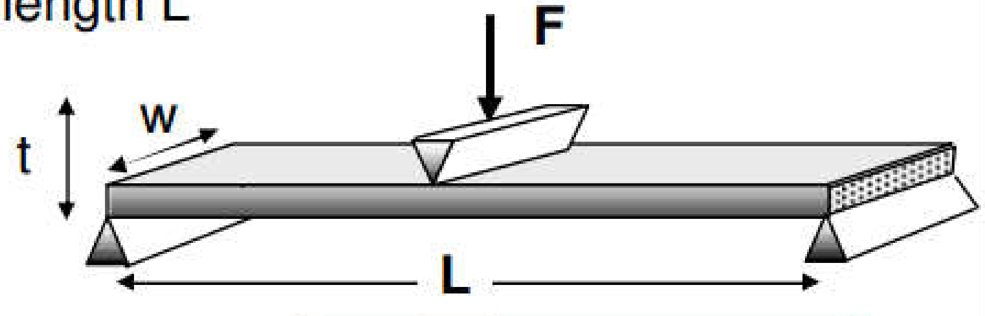
$$m = \left(\frac{12\, S\, L^5}{C}\right)^{1/2} \left(\frac{\rho}{E^{1/2}}\right)$$

Chose materials with smallest $\left(\frac{\rho}{E^{1/2}}\right)$

Ref: www.diim.unict.it/users/fgiudice/pdfs/SM_2.3.pdf

Deriving Performance Indices: Light, stiff panel

Function *Panel* with given width w and length L



Objective *Minimise mass*, m, where

$$m = A L \rho = w\ t\ L \rho$$

Constraint *Stiffness* of the panel S:

$$S = \frac{C E I}{L^3}$$

I is the second moment of area:

$$I = \frac{w t^3}{12}$$

- m = mass
- w = width
- L = length
- ρ = density
- t = thickness
- S = stiffness
- I = second moment of area
- E = Youngs Modulus

Free variables
- *Material choice.*
- *Panel thickness t.* Combining the equations gives:

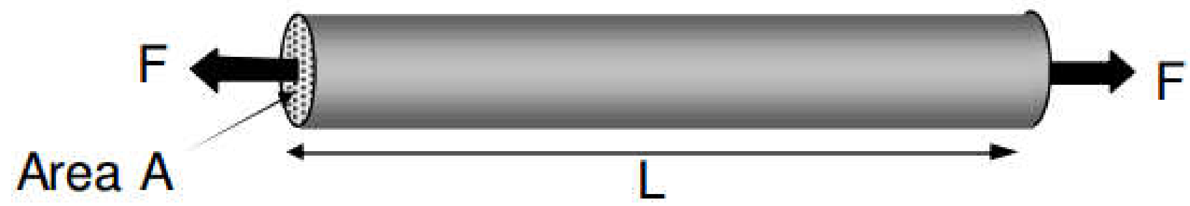
$$m = \left(\frac{12\ S\ w^2}{C}\right)^{1/3} L^2 \left(\frac{\rho}{E^{1/3}}\right)$$

Chose materials with smallest $\left(\frac{\rho}{E^{1/3}}\right)$

Ref: www.diim.unict.it/users/fgiudice/pdfs/SM_2.3.pdf

Deriving Performance Indices: Light, strong tie

Strong tie of length L and minimum mass



Function — *Tie-rod*

Objective — *Minimise mass m:*

$$m = A\,L\,\rho \qquad (1)$$

Constraints

- *Length L is specified*
- *Must not fail under load F*
- *Adequate fracture toughness*

Equation for constraint on A:

$$F/A < \sigma_y \qquad (2)$$

Free variables

- *Material choice*
- *Section area A; eliminate in (1) using (2):*

$$m = FL\left(\frac{\rho}{\sigma_y}\right)$$

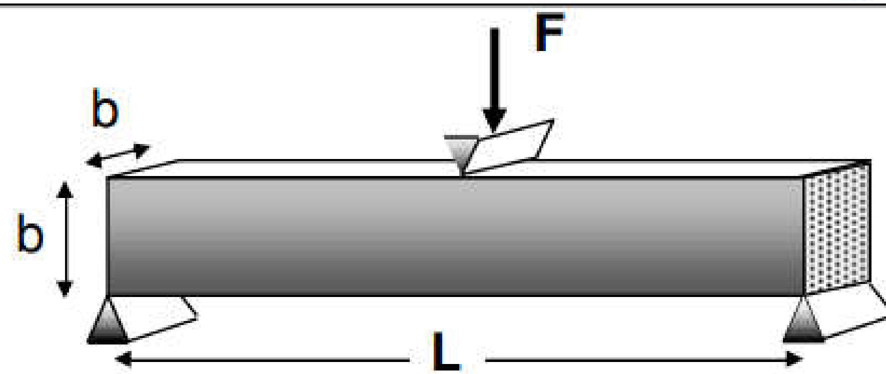
m = mass
A = area
L = length
ρ = density
σ_y = yield strength

STEP 4

Use this constraint to eliminate the free variable in performance equation

Ref: www.diim.unict.it/users/fgiudice/pdfs/SM_2.3.pdf

Deriving Performance Indices: Light, strong beam



Function — *Beam* (solid square section).

Objective — *Minimise mass*, m, where:

$$m = AL\rho = b^2 L\rho$$

Constraint — *Must not fail under load F*

$$\sigma_y > \frac{M \cdot b/2}{I} \left(= \frac{3FL}{b^3} \right)$$

I is the second moment of area:

$$I = \frac{b^4}{12}$$

m = mass
A = area
L = length
ρ = density
b = edge length
I = second moment of area
σ_y = yield strength

Free variables
- *Material choice.*
- *Edge length b.* Combining the equations gives:

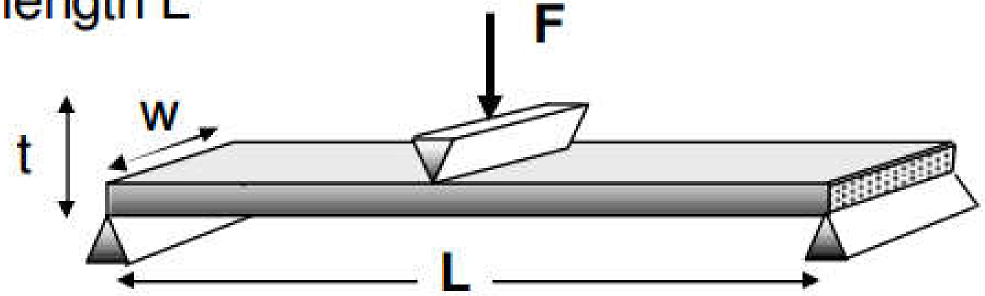
$$m = (L)^{5/3} (3F)^{2/3} \left(\frac{\rho}{\sigma_y^{\,2/3}} \right)$$

Chose materials with smallest $\left(\frac{\rho}{\sigma_y^{\,2/3}} \right)$

Ref: www.diim.unict.it/users/fgiudice/pdfs/SM_2.3.pdf

Deriving Performance Indices: Light, strong panel

Function *Panel* with given width w and length L



Objective *Minimise mass*, m, where

$$m = A L \rho = w\ t\ L \rho$$

Constraint *Must not fail under load F*

$$\sigma_y > \frac{M \cdot t/2}{I} \left(= \frac{3FL}{wt^2} \right)$$

I is the second moment of area:

$$I = \frac{w t^3}{12}$$

m = mass
w = width
L = length
ρ = density
t = thickness
I = second moment of area
σ_y = yield strength

Free variables
- *Material choice.*
- *Panel thickness t.* Combining the equations gives:

$$m = (3Fw)^{1/2} (L)^{3/2} \left(\frac{\rho}{\sigma_y^{1/2}} \right)$$

Chose materials with smallest $\left(\frac{\rho}{\sigma_y^{1/2}} \right)$

Ref: www.diim.unict.it/users/fgiudice/pdfs/SM_2.3.pdf

Performance Indices for weight: Stiffness

Material properties --

the "Physicists" view of materials, e.g.

Cost,	C_m
Density,	ρ
Modulus,	E
Strength,	σ_y
Endurance limit,	σ_e
Thermal conductivity,	λ
T- expansion coefficient,	α

Material indices --

the "Engineers" view of materials

Objective: minimise mass

Function	**Stiffness**	**Strength**
Tension (tie)	ρ/E	ρ/σ_y
Bending (beam)	$\rho/E^{1/2}$	$\rho/\sigma_y^{2/3}$
Bending (panel)	$\rho/E^{1/3}$	$\rho/\sigma_y^{1/2}$

Minimise these!

Ref: www.diim.unict.it/users/fgiudice/pdfs/SM_2.3.pdf