Material Selection

ME 310: Mechanical Design

Sappinandana Akamphon

Department of Mechanical Engineering, TSE

Outline

Overview of Material Selection

Engineering Materials}

Material Selection Considerations

Material Selection Procedure

Material Selection

- Plenty of materials out there
- Where do we start?
- What are the criteria to consider?

Material Selection Criteria}

- Mechanical properties: strength, stiffness, ..
- Thermal properties
- Costs
- etc.

Outline

Steels

- The most used material for machine components
- It has been used for very long time, so behaviors are well understood
- Compositions, thermal treatment and mechanical treatment can be used to obtain wide range of properties.

Basic Steel Selection Criteria}

- All steels have the same Young's moduli $\rightarrow$ if stiffness is key, then choose the cheapest steel.
- Carbon content determines the hardness. More carbon, harder steel.

Heat Treatment of Steel Alloy}

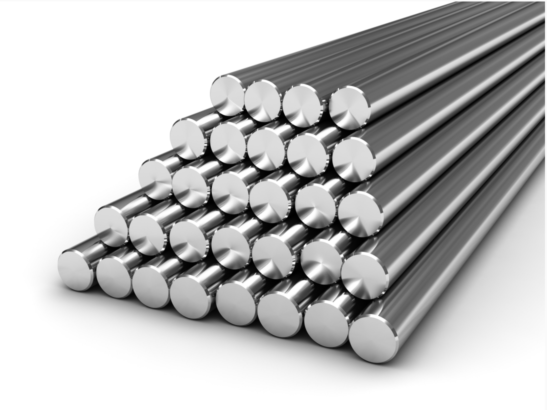
- Parts can be heat-treated to obtain the same hardness with plain carbon steel as with more expensive alloys.
- Alloying elements helps hardening. Hardness can be improved with less extreme heat treatments.

Case-Hardening Steels}

Hardening of the surface, usually by carburizing, cyaniding, nitriding or induction hardening.

- Carburizing introduces additional carbon into steel and apply heat treatment.
- Cyaniding introduces both carbon and nitrogen.
- Nitriding adds nitrogen to the part surface at lower than 1000° F or less so there is no risk of warpage.
- Induction and flame hardening heat the surface then quench and temper.

Stainless Steels



- Contains a minimum of 10.5\
- Heat-resistant and corrosion-resistant.
- 3-5 times more expensive

Iron-based Superalloys

- For high-temperature applications: gas turbines, jet engines, heat exchangers, furnaces …
- Strength at high temp and resistance to creep, corrosion, and wear.

Aluminum Alloys

- Slightly weaker but much lighter than steel
- Difficult to harden
- Lower geometric stabilility than steel.
- Much easier to cast and machine.

Copper Alloy

- Copper & Brass
- Excellent thermal and electrical conductivity. Good resistance to corrosion.
- Poor strength.

Other interesting alloys

Magnesium Lightest engineering metal.

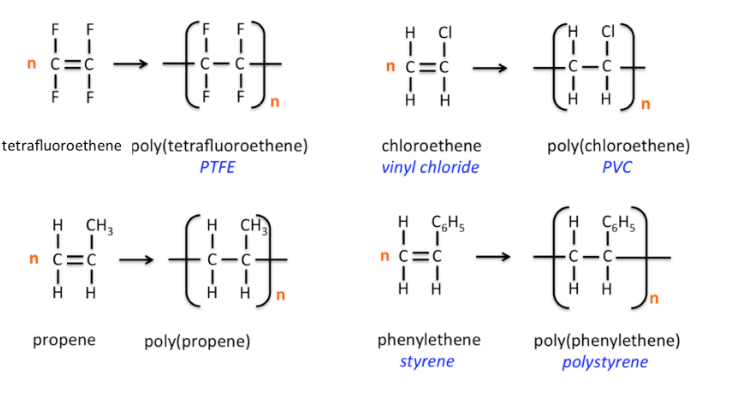
Nickel strong and tough at extreme temperatures.

Titanium extremely corrosion-resistance, low thermal conductivity and good strength-weight ratio. Expensive and difficult to machine.

Zinc inexpensive. Easy to die-cast. Moderate strength.

Overview of Plastics

- Polymers form from small *monomers*



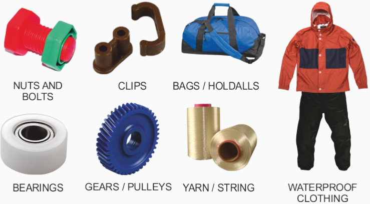
Plastic Properties

- More monomers $\rightarrow$ heavier molecules $\rightarrow$ gas, liquid, solid
- Side branching leads to less packing and lower density, but also higher geometric stability and stiffness.
- Divided on reaction to heat: thermoset (not softening) and thermoplastic (softening)

Thermoplastics

Polyester Excellent dimensional stability, electrical resistance, and toughness. Poor in outdoor and high temperature useage.

Polyethylene Lightweight. Easy to process. Inexpensive. Wide variety of grades from LDPE, MDPE, and HDPE. (Water bottle)



Thermoplastics II

Polypropylene Outstanding resistance to flex and stress cracking. Lightweight. Low cost. (Plastic bag)

Polystyrene Low-cost, clear, brittle. (Clear plastic box and covers.)

Polyurethane Tough, abrasion-resistant, and impact-resistant. (Resin floor coating)

PVC low cost. Many formulations available. Hard, tough, and good electrical resistance. Good outdoor stability and resistance to moisture.

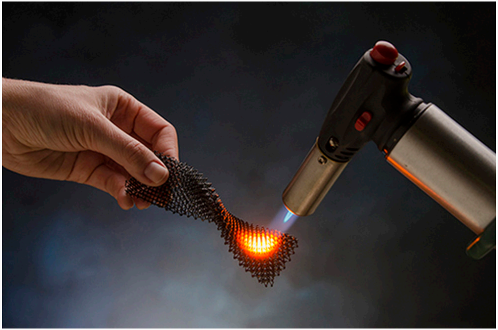
Thermoset

Amino Abrasion and chip-resistant. Resistance to solvent. Melamine is hard and has high heat and chemical resistance.

Epoxy Exceptional mechanical strength and adhesion. (Epoxy glue)

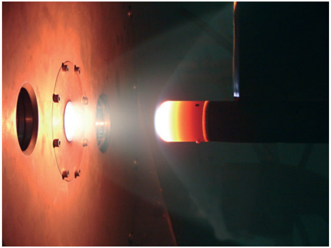
Silicone Compatible with body tissue. High costs.

Engineering Ceramics



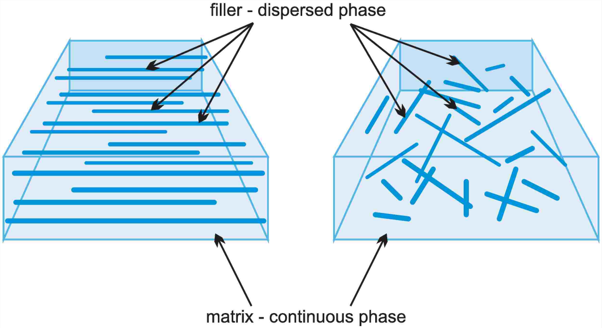
- Oxides, carbides, and nitrides
- Extremely high temperature
- High compressive strength, but brittle

Examples of Engineering Ceramics

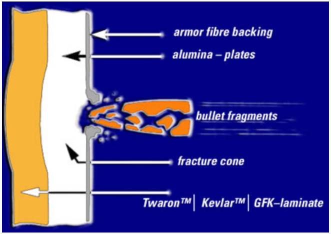


Engineering Composites

- Combine strengths of different materials.
- CFRP, Steel-reinforced concrete, GFRP, etc.
- Typically matrix + fibers



Examples of Composites

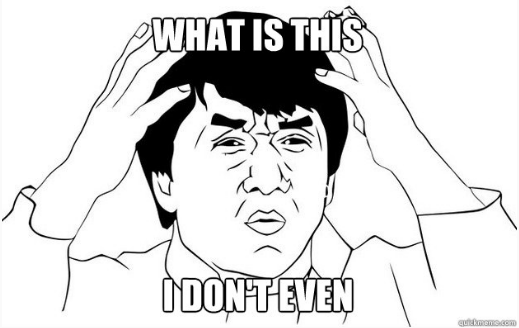


Outline

Factors

Availability	How easy it is to obtain or buy
Cost	Raw material cost
Properties	Strengths and weaknesses
Processes	material - properties - processes are linked
Formability	How easy it is to shape into desired components.
Finishing	Enhance the properties for inexpensive materials.

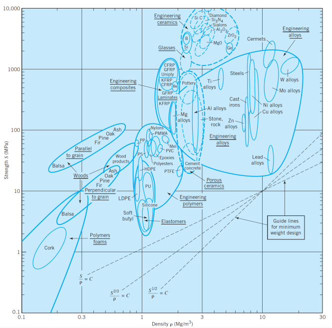
Material Selection Charts

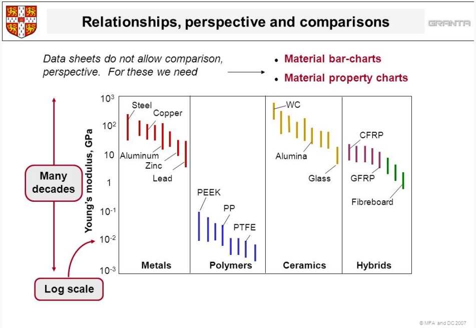


- Too many materials to browse through
- Needs a way to quickly assess multiple material properties
- Material selection charts!

Material Selection Charts

- Invented by M.F. Ashby in 1993, the charts map multiple materials together by their properties.
- More details in *Materials selection in mechanical design* (M. F. Ashby)
- Bubble charts and bar charts





Outline

The procedure

- Establish required service performances
- Select a suitable material
- Make a final evaluation
- Test, a lot of tests

Establish Required Performance

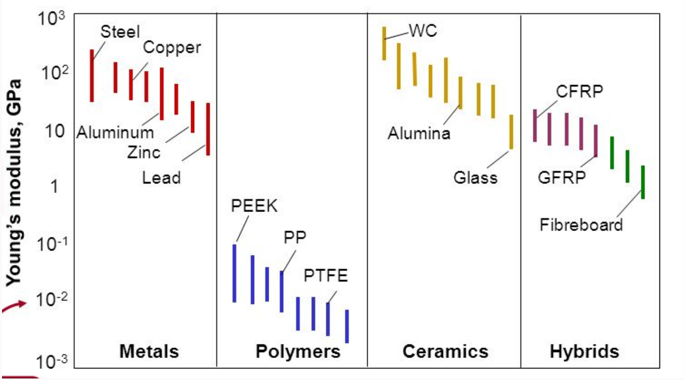
- Determine the operational conditions of the component
- Translate into material properties.

Beam for swing set
deflection $\leq$ 2 cm
Max weight = 300 kg

$\longrightarrow$

E = 150 GPa
σ_y = 300 MPa

Select a Suitable Material}



- Looking through data sheets is not fun
- Material charts are much better

Make a Final Evaluation}

- Select the best material for the application
- 'Best' is the material with the best value, defined simply as the material selection index (SI) where

$$SI = \frac{\text{(availability)(performance)}}{\text{total cost}}$$

Test, test, and more test}

- Test in operating conditions.
- Do we need more tests?
- Reevaluate the risk and uncertainty of chosen material, for example, cost of product failure.

Example: Minimum Weight Bar}

Design a lightest possible tensile bar that can take $F_{\mathsf{max}} = 50000$ N.
We have 3 material choices.

Material	Density	Yield Strength
HSS	7800	1200
Aluminum	2300	400
CFRP	1500	350

The Hard Way

Let's assume $N_s = 2$. The cross-sectional area required for each material is

$$N_s = \frac{S_y}{\frac{F}{A}}$$

$$A = \frac{N_S F}{S_y}$$

HSS	8.33e-05 m^2
Aluminum	2.50e-04 m^2
CFRP	2.86e-04 m^2

Comparing mass

Once cross-sectional areas are obtained, mass is just

$$m = \rho A l$$

Material	Mass (kg)
HSS	6.50e-01 l
Aluminum	5.75e-01 l
CFRP	4.29e-01 l

So CFRP is the lightest, regardless of length l.

The 'Easy' Way

Combine the equations for area and mass

$$
\begin{aligned}
m &= \rho A l \\
&= \rho N_s \frac{F}{S_y} l
\end{aligned}
$$

Well, N_s, F, and l are all given by the problem

Strength - Weight Ratio

We simply need to determine a single ratio

$$m \sim \frac{\rho}{S_y}$$

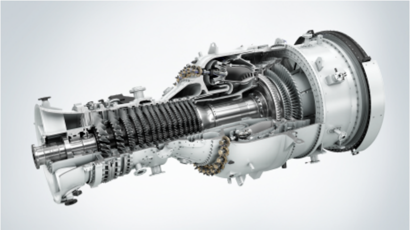
to identify the lightest material for the application

Minimum weight index

Guideline for strength-based minimum weight design

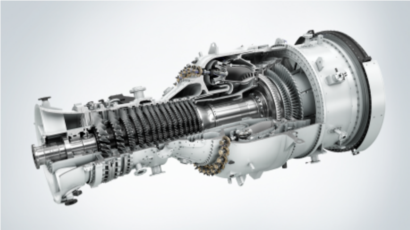
Load condition	Min weight index
Tension	$\dfrac{S_y}{\rho}$
Bending, torsion	$\dfrac{S_y^{2/3}}{\rho}$
Plate under normal load	$\dfrac{S_y^{1/2}}{\rho}$

Example: Material for a Gas Turbine Shaft



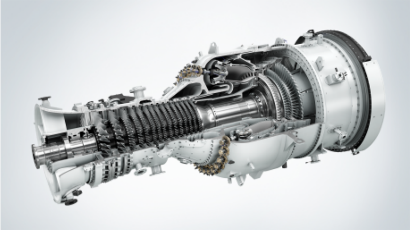
- What material properties should be considered?

Example: Material for a Gas Turbine Shaft



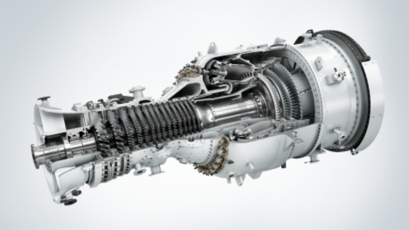
- What material properties should be considered?
  - mass / density

Example: Material for a Gas Turbine Shaft



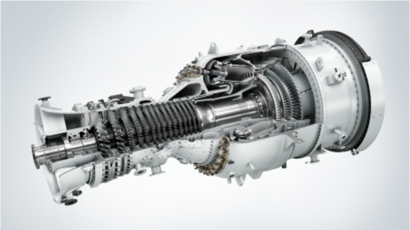
- What material properties should be considered?
  - mass / density - strength

Example: Material for a Gas Turbine Shaft



- What material properties should be considered?
  - mass / density - strength - temperature

Example: Material for a Gas Turbine Shaft



- What material properties should be considered?
  - mass / density - strength - temperature - cost

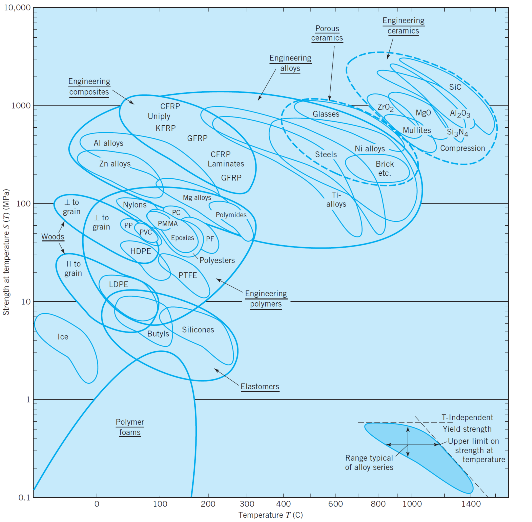
Establish required performances

- Shaft as light as possible
- Operating temperature $> 300ˆ$C
- Cost is not a concern

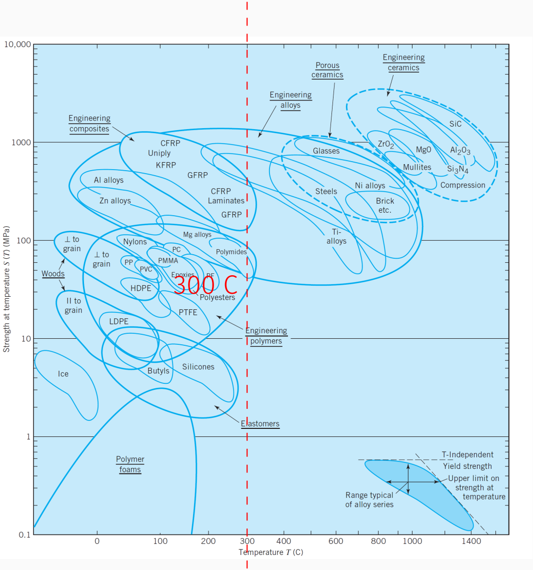
Establish required performances

- Shaft as light as possible $\rightarrow$ strength - density diagram
- Operating temperature $> 300^$C $\rightarrow$ strength - temp diagram
- Cost is not a concern $\rightarrow$ yay?

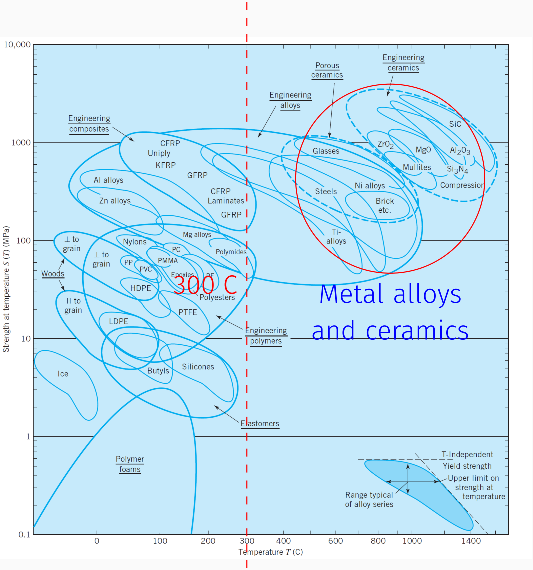
Can you stand the heat?



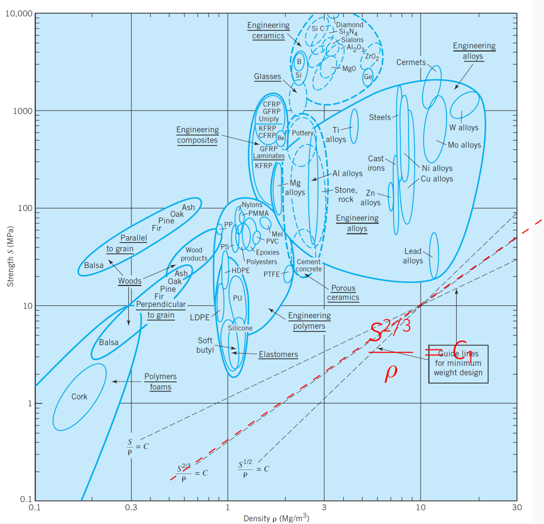
Can you stand the heat?



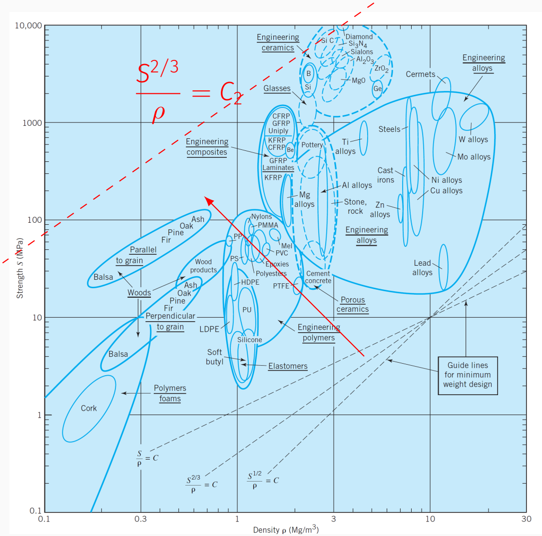
Can you stand the heat?



Minimize the weight



Minimize the weight

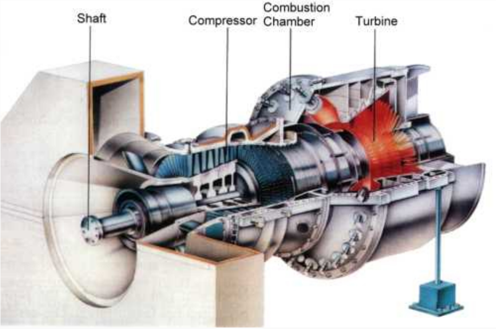


Combine the results

- Light shaft $\rightarrow$ ceramics, woods // to grains, composites, and metal alloys
- High temperature operation NOT OK $\rightarrow$ woods, composites, Zn, Al, and Mg alloys
- Preliminary choices $\rightarrow$ ceramics, Ti, Ni, and Steel alloys

Additional evaluations

- 1st choice - ceramics
  - Hard to machine
  - Brittle
- 2nd choice - Ti, Ni, or Steels
- Test (simulation or prototype) to obtain final choice



Any Questions?