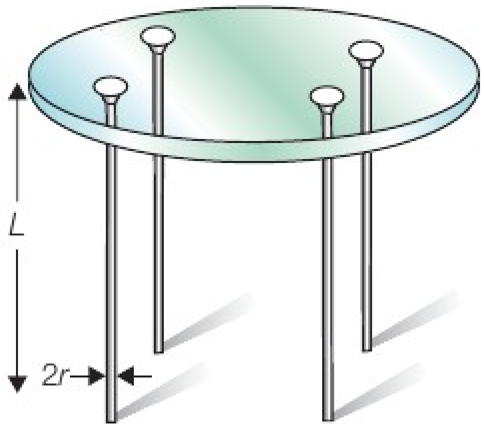
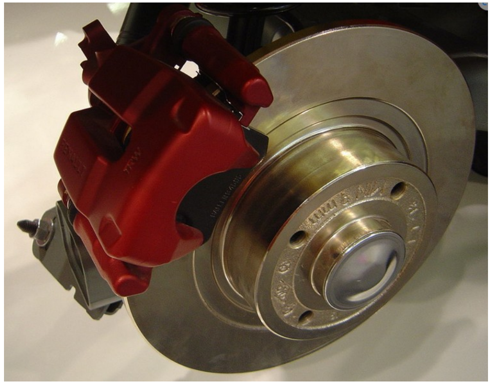
Material Selection Examples



A lightweight table consists of flat sheet of toughened glass supported on slender, unbraced cylindrical legs. The legs must be solid (to make them thin) and as light as possible (to make the table easier to move). They must support the table top and whatever is placed upon it without buckling. What materials could one recommend?



What is the best choice of material for a shaft? What is the best choice of material for the brake disc of a car

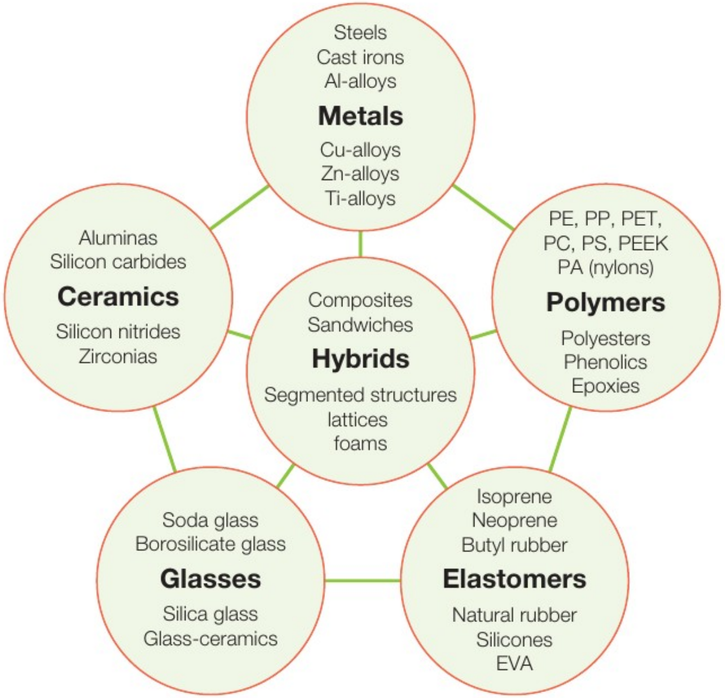
https://www.sandvik.coromant.com/en-us/industry-solutions/automotive/transmission/shafts

Selection of Materials in Mechanical Design

Factors to Consider While Selecting a Material

- Nature of loading on the component
- Expected stress state at the critical locations
- Allowable deformations at the critical locations
- Interfaces with other components of the product
- Environment in which the component is expected to operate.
- Physical size and weight of the component
- Aesthetics expected of the component/product
- Cost target of the component/product
- Availability of anticipated manufacturing processes

Material Families



http://www.matweb.com

Primary Reference
Ashby, Material Selection in Mechanical Design

Design Limiting Material Properties

Class	Property	Symbol and units	
General	Density	ρ	(kg/m^3 or Mg/m^3)
	Price	C_m	(\$/kg)
Mechanical	Elastic moduli (Young's, shear, bulk)	E, G, K	(GPa)
	Yield strength	σ_y	(MPa)
	Ultimate strength	σ_u	(MPa)
	Compressive strength	σ_c	(MPa)
	Failure strength	σ_f	(MPa)
	Hardness	H	(Vickers)
	Elongation	ε	(–)
	Fatigue endurance limit	σ_e	(MPa)
	Fracture toughness	K_{IC}	(MPa.m$^{1/2}$)
	Toughness	G_{IC}	(kJ/m^2)
	Loss coefficient (damping capacity)	η	(–)
Thermal	Melting point	T_m	(C or K)
	Glass temperature	T_g	(C or K)
	Maximum service temperature	T_{max}	(C or K)
	Minimum service temperature	T_{max}	(C or K)
	Thermal conductivity	λ	(W/m.K)
	Specific heat	C_p	(J/kg.K)
	Thermal expansion coefficient	α	(K^{-1})
	Thermal shock resistance	ΔT_s	(C or K)
Electrical	Electrical resistivity	ρ_e	(Ω.m or $\mu\Omega$.cm)
	Dielectric constant	ε_d	(–)
	Breakdown potential	V_b	(10^6 V/m)
	Power factor	P	(–)
Optical	Optical, transparent, translucent, opaque	Yes/No	
	Refractive index	n	(–)
Eco-properties	Energy/kg to extract material	E_f	(MJ/kg)
	CO_2/kg to extract material	CO_2	(kg/kg)
Environmental resistance	Oxidation rates	Very low, low, average, high, very high	
	Corrosion rates		
	Wear rate constant	K_A	MPa^{-1}

Ashby, Material Selection in Mechanical Design

Important Mechanical Properties of Engineering Materials

- Ductility: It is the ability to undergo inelastic deformation before failure. It is measured in terms of elongation (tensile strain at failure)

- Elastic Modulus (GPa) – measure of stiffness

- Resilience: The ability of a material to absorb energy per unit volume without permanent deformation is called its resilience U_R (also called modulus of resilience) and is equal to the area under the stress-strain curve up to the elastic limit

- Toughness: The ability of a material to absorb energy per unit volume without fracture is called its toughness U_T (also called modulus of toughness) and is equal to the area under the stress-strain curve up to the fracture point

- Fracture toughness($MPa\sqrt{m}$) It is is a material property that defines its ability of a material to resist crack growth and is denoted by K_c

Important Mechanical Properties of Engineering Materials

- Hardness – the resistance of a material to penetration by a pointed tool (Rockwell hardness, Brinell hardness). For steel: $\sigma_{ult} = 3.40 H_B$ (MPa)

- Machinability – related to the ease with which the material can be machined to a good surface finish with a reasonable tool life

- Creep – progressive elongation experienced by materials when subjected to high stress (less than yield strength) at high temperatures. (T $>$ 0.3 Tm)

Important Thermal Properties of Engineering Materials

- Coefficient of Thermal Expansion (K^{-1}) – The thermal strain per degree of temperature change is measured by the coefficient of thermal expansion

- Thermal Conductivity (W/m.K) – indicates the ability to conduct/transfer heat at steady state

- Thermal Diffusivity (m^2/s) . It is given by $\alpha = \lambda/\rho C_p$. The distance x the heat diffuses in time t is given by $x \approx \sqrt{2\alpha t}$

- Heat capacity or Specific heat (units J/kg.K) It is the energy required to heat 1 kg of a material by 1 K. The measurement is usually done at constant pressure for solids

Metals

- Metals have relatively high elastic moduli.
- Are good conductors of heat and electricity
- Are soft and easily deformed when pure and cane be made strong by alloying and heat treatment
- Metals are ductile and yield before they fracture
- Metals are susceptible to fatigue failure
- Of all material families, they are the least resistant to corrosion

Ceramics

- Ceramics, have high moduli, but, unlike metals, they are brittle.
- Their crushing strength is much higher fracture strength.
- They are hard and abrasion-resistant (hence their use for bearings and cutting tools);
- They retain their strength to high temperatures (they are used as thermal-barrier coatings on aircraft turbine blades)
- They resist corrosion well (thus their use as toilets, basins and kitchen work-surfaces).
- Are poor conductors of heat and electricity
- They have a low tolerance for stress concentrations (like holes or cracks) or for high contact stresses (at clamping points, for instance).
- Ceramics always have a wide scatter in strength and the strength itself depends on the volume of material under load.
- Ceramics cannot be reshaped easily
- Design with ceramics is more difficult than design with metals.

Ceramics & Glasses

Glass is made of inorganic, non-metallic materials with an amorphous structure

Ceramics are by definition natural or synthetic inorganic, non-metallic, polycrystalline materials

Typical properties of ceramics

- High hardness
- High elastic modulus
- Low ductility
- High dimensional stability
- Good wear resistance
- High resistance to corrosion and chemical attack
- High weather resistance
- High melting point
- High working temperature
- Low thermal expansion
- Low to medium thermal conductivity
- Good electrical insulation
- Low to medium tensile strength
- High compressive strength
- Medium machinability
- Opacity
- Brittleness
- Poor impact strength
- Low thermal shock resistance

Typical properties of glasses

- High hardness
- High elastic modulus
- Low ductility
- Good dimensional stability
- Good wear resistance
- High resistance to chemicals
- High weather resistance
- Relatively high melting point
- Relatively high working temperature
- Relatively low coefficient of thermal expansion
- Very low thermal conductivity
- Good electrical insulation
- Low tensile strength
- High compressive strength
- Poor machinability, but can be blown, drawn or laminated
- High transparency
- High brittleness
- Poor impact strength
- Low thermal shock resistance

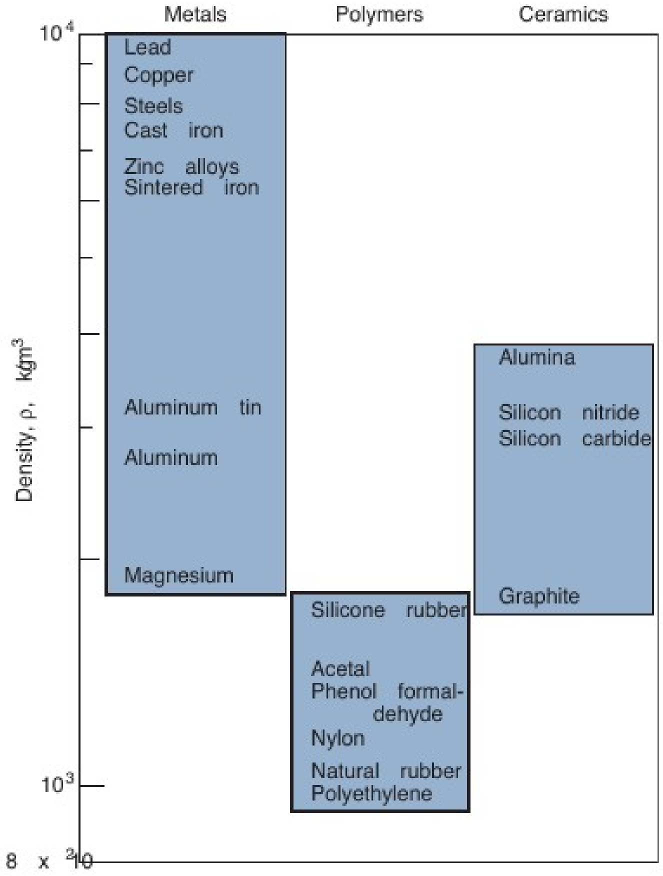
Both have a low tolerance for stress concentrations (like holes or cracks) or for high contact stresses (at clamping points, for instance).

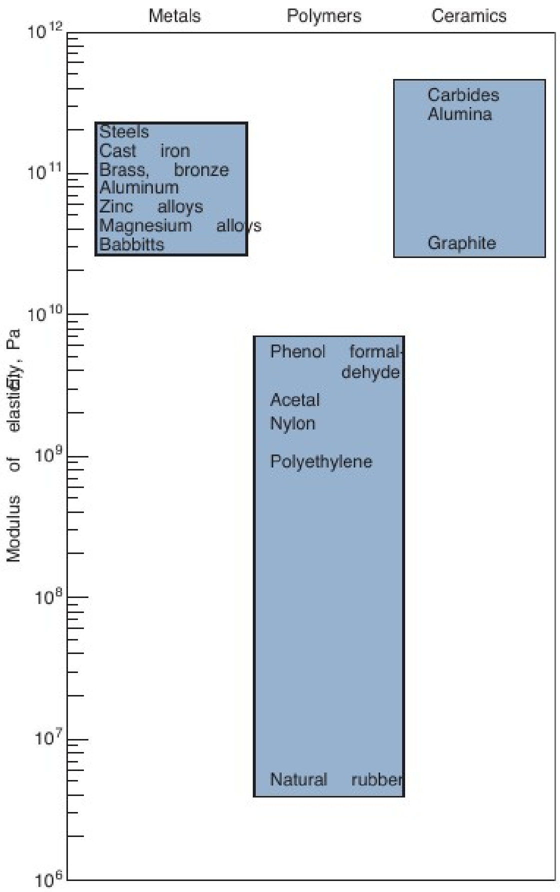
https://ceramics.org/about/what-are-engineered-ceramics-and-glass/structure-and-properties-of-ceramics/

Polymers

- Polymers have low moduli, roughly 50 times lower than those of metals, but they can be strong -nearly as strong as metals (elastic deflections can be large)
- When combinations of properties, such as strength per unit weight, are important, polymers can compete with metals
- They are easy to shape
- Assembling polymer components is fast and cheap.
- By accurately sizing the mold and precoloring the polymer, no finishing operations are needed.
- Polymers resist corrosion and have low coefficients of friction.
- They creep even at room temperature and their properties depend on temperature
- Few have useful strength above 200°C.
- They have low thermal conductivity

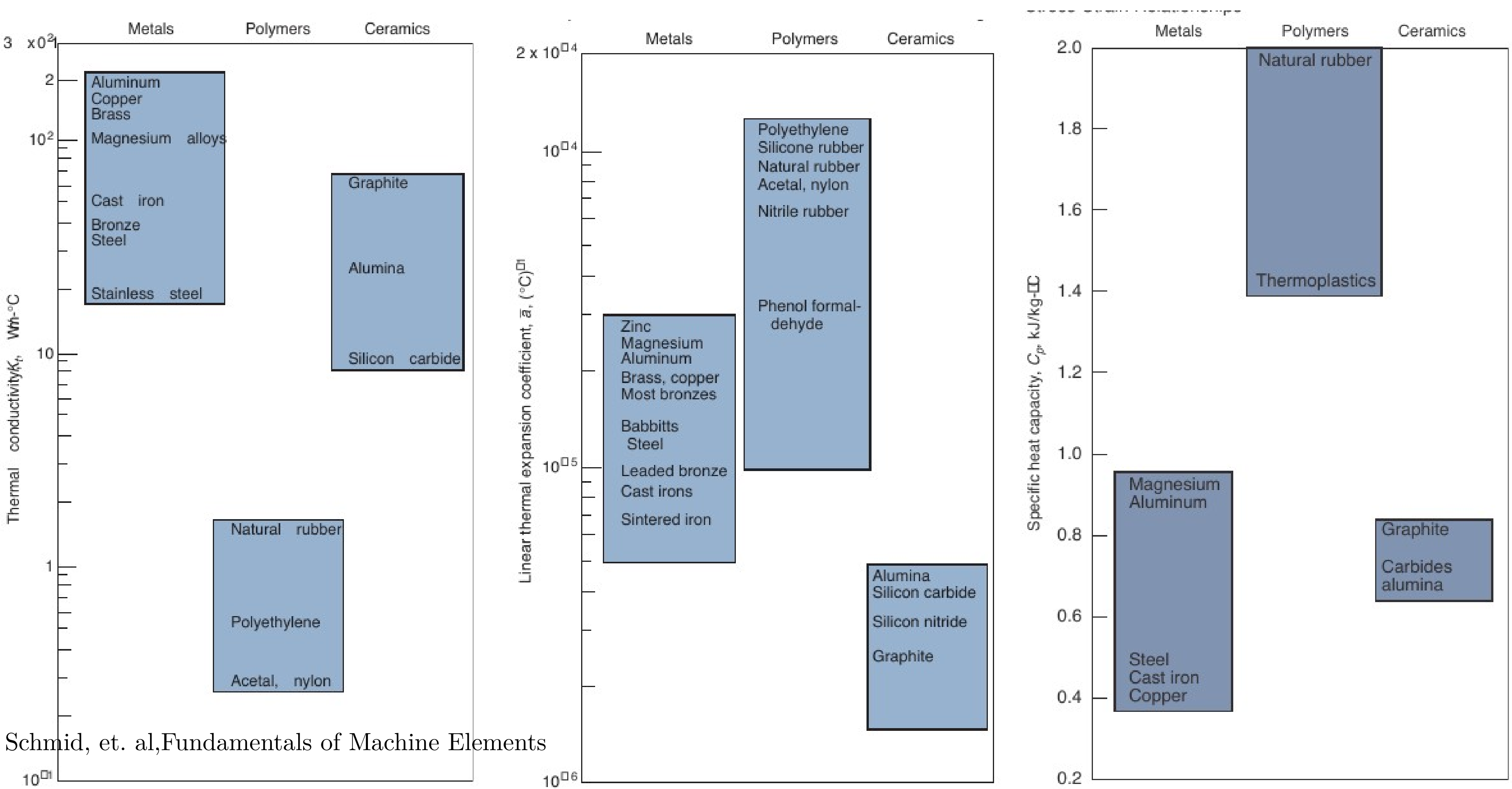
Comparison of Properties of Metals, Polymers & Ceramics





Schmid, et. al, Fundamentals of Machine Elements

Comparison of Thermal Properties of Metals, Polymers & Ceramics



Schmid, et. al,Fundamentals of Machine Elements

AISI/SAE Designation of Steel Alloys

Type	AISI/SAE Series	Principal Alloying Elements
Carbon Steels		
Plain	10xx	Carbon
Free-cutting	11xx	Carbon plus Sulphur (resulphurized)
Alloy Steels		
Manganese	13xx	1.75% Manganese
	15xx	1.00 to 1.65% Manganese
Nickel	23xx	3.50% Nickel
	25xx	5.00% Nickel
Nickel-Chrome	31xx	1.25% Nickel and 0.65 or 0.80% Chromium
	33xx	3.50% Nickel and 1.55% Chromium
Molybdenum	40xx	0.25% Molybdenum
	44xx	0.40 or 0.52% Molybdenum
Chrome-Moly	41xx	0.95% Chromium and 0.20% Molybdenum
Nickel-Chrome-Moly	43xx	1.82% Nickel, 0.50 or 0.80% Chromium, and 0.25% Molybdenum
	47xx	1.45% Nickel, 0.45% Chromium, and 0.20 or 0.35% Molybdenum
Nickel-Moly	46xx	0.82 or 1.82% Nickel and 0.25% Molybdenum
	48xx	3.50% Nickel and 0.25% Molybdenum
Chrome	50xx	0.27 to 0.65% Chromium
	51xx	0.80 to 1.05% Chromium
	52xx	1.45% Chromium
Chrome-Vanadium	61xx	0.60 to 0.95% Chromium and 0.10 to 0.15% Vanadium minimum

AISI – American Iron and Steel Institute

SAE – Society of Automotive Engineers

Last two digits indicate the % of carbon present.

e.g. 1040 – plain carbon steel with 0.40 % carbon (0.37% - 0.43%

Aluminum Association Designation of Wrought Aluminum Alloys

Series	Major Alloying Elements	Secondary Alloys
1xxx	Commercially pure (99%)	None
2xxx	Copper (Cu)	Mg, Mn, Si
3xxx	Manganese (Mn)	Mg, Cu
4xxx	Silicon (Si)	None
5xxx	Magnesium (Mg)	Mn, Cr
6xxx	Magnesium and Silicon	Cu, Mn
7xxx	Zinc (Zn)	Mg, Cu, Cr
Hardness Designations		
xxxx-F	As fabricated	
xxxx-O	Annealed	
xxxx-Hyyy	Work hardened	
xxxx-Tyyy	Thermal/age hardened	

Wrought alloys are formed by rolling, forging and extrusion into useful products

The firs digit indicates the major alloying element The second digit if not 0, indicates if the alloy is a variation of the original alloy, i.e., alloy 6160 is the first variation of alloy 6060. The third and four digits are assigned arbitrarily to identify alloys in their respective series, except for the 1xxx series alloys, where the last two digits describe the aluminum purity in the alloy.

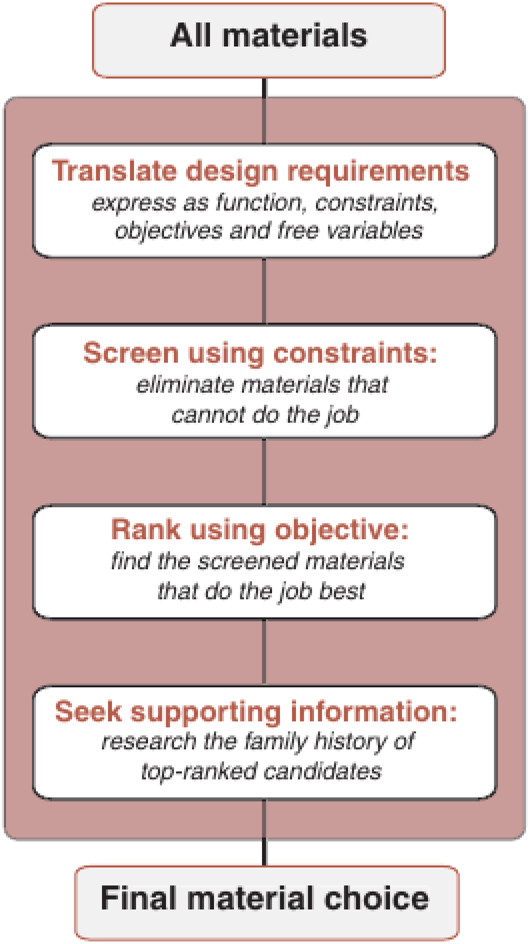
Material Families and Classes

Family	Classes	Short name
Metals (the metals and alloys of engineering)	Aluminum alloys	Al alloys
	Copper alloys	Cu alloys
	Lead alloys	Lead alloys
	Magnesium alloys	Mg alloys
	Nickel alloys	Ni alloys
	Carbon steels	Steels
	Stainless steels	Stainless steels
	Tin alloys	Tin alloys
	Titanium alloys	Ti alloys
	Tungsten alloys	W alloys
	Lead alloys	Pb alloys
	Zinc alloys	Zn alloys
Ceramics	Alumina	Al_2O_3
Technical ceramics (fine ceramics capable of load-bearing application)	Aluminum nitride	AlN
	Boron carbide	B_4C
	Silicon Carbide	SiC
	Silicon Nitride	Si_3N_4
	Tungsten carbide	WC
Non-technical ceramics (porous ceramics of construction)	Brick	Brick
	Concrete	Concrete
	Stone	Stone
Glasses	Soda-lime glass	Soda-lime glass
	Borosilicate glass	Borosilicate glass
	Silica glass	Silica glass
	Glass ceramic	Glass ceramic
Polymers (the thermoplastics and thermosets of engineering)	Acrylonitrile butadiene styrene	ABS
	Cellulose polymers	CA
	Ionomers	Ionomers
	Epoxies	Epoxy
	Phenolics	Phenolics
	Polyamides (nylons)	PA
	Polycarbonate	PC
	Polyesters	Polyester
	Polyetheretherkeytone	PEEK
	Polyethylene	PE
	Polyethylene terephalate	PET or PETE
	Polymethylmethacrylate	PMMA
	Polyoxymethylene (Acetal)	POM
	Polypropylene	PP
	Polystyrene	PS
	Polytetrafluorethylene	PTFE
	Polyvinylchloride	PVC

Family	Classes	Short name
Elastomers (engineering rubbers, natural and synthetic)	Butyl rubber	Butyl rubber
	EVA	EVA
	Isoprene	Isoprene
	Natural rubber	Natural rubber
	Polychloroprene (Neoprene)	Neoprene
	Polyurethane	PU
	Silicone elastomers	Silicones
Hybrids	Carbon-fiber reinforced polymers	CFRP
Composites	Glass-fiber reinforced polymers	GFRP
	SiC reinforced aluminum	Al-SiC
Foams	Flexible polymer foams	Flexible foams
	Rigid polymer foams	Rigid foams
Natural materials	Cork	Cork
	Bamboo	Bamboo
	Wood	Wood

Ashby, Material Selection in Mechanical Design

Material Selection Procedure



- **Translation** – Converting the design requirements into constraints and objectives that can be applied to the materials database
- **Screening** – Eliminating materials that do not meet the constraints
- **Ranking** – Ordering the remaining materials by their ability to meet the objective
- **Documentation** – In depth study of the materials identified by ranking

Ashby, Material Selection in Mechanical Design

Translation

- **Function**: What does the component do ?
- **Constraints**: What non-negotiable constraints must be met ?
- **Objective**: What is to be minimized or maximized ?
- **Free Variable**: What parameters of the problem is the designer free to change ?

Common Constraints:

Meet the target value:

Stiffness

Strength

Fracture toughness

Thermal conductivity

Electrical resistivity

Cost

Mass

Common Objectives:

Minimize:

Volume

Heat loss

Cost

Mass

Maximize

Energy storage

Heat flow

Material Index

- **Material index**: group of material properties which govern some aspect of performance of the component
- The material is selected by maximizing/minimizing the **material index**

Function, objective, and constraints	Index
Tie, minimum weight, stiffness prescribed	$\frac{E}{\rho}$
Beam, minimum weight, stiffness prescribed	$\frac{E^{1/2}}{\rho}$
Beam, minimum weight, strength prescribed	$\frac{\sigma_y^{2/3}}{\rho}$
Beam, minimum cost, stiffness prescribed	$\frac{E^{1/2}}{C_m \rho}$
Beam, minimum cost, strength prescribed	$\frac{\sigma_y^{2/3}}{C_m \rho}$
Column, minimum cost, buckling load prescribed	$\frac{E^{1/2}}{C_m \rho}$
Spring, minimum weight for given energy storage	$\frac{\sigma_y^2}{E \rho}$
Thermal Insulation, minimum cost, heat flux prescribed	$\frac{1}{\lambda C_p \rho}$
Electromagnet, maximum field, temperature rise prescribed	$\frac{C_p \rho}{\rho_e}$

ρ = density; E = Young's modulus; σ_y = elastic limit; C_m = cost/kg λ = thermal conductivity; ρ_e = electrical resistivity; C_p = specific heat.

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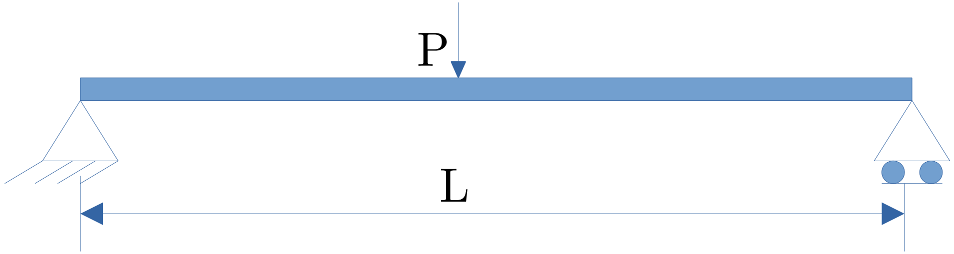
Example

Choose a material for a simply supported light stiff beam with a <u>square c/s</u>. The stiffness of the beam should be at least S^*



Material	ρ(kg/m³)	E(GPa)	σ_y(MPa)
1020 Steel	7850	205	320
6061 Al	2700	70	120
Ti-6Al-4V	4400	115	950
GFRP	1750	28	300

Function: The beam supports a load P

Constraint: stiffness should be at least S^*

Objective: minimize the mass of the beam

Free variable: material and c/s area A

$$\delta = \frac{PL^3}{48EI}, \; I = \frac{b^4}{12}$$

$$\text{Stiffness} \quad S = \frac{P}{\delta} = \frac{48EI}{L^3} = \frac{4EA^2}{L^3}$$

Example

Mass $m = \rho A L$

Stiffness $S = \dfrac{4EA^2}{L^3}$

$S \geq S^*$ constraint

$$\frac{4EA^2}{L^3} \geq S^*$$

$$\frac{4Em^2}{L^5\rho^2} \geq S^*$$ Substitute for the area A in terms of mass m

or $$m \geq \left(\frac{1}{2}\sqrt{S^*}\right)\left(L^{5/2}\right)\left(\frac{\rho}{E^{1/2}}\right)$$

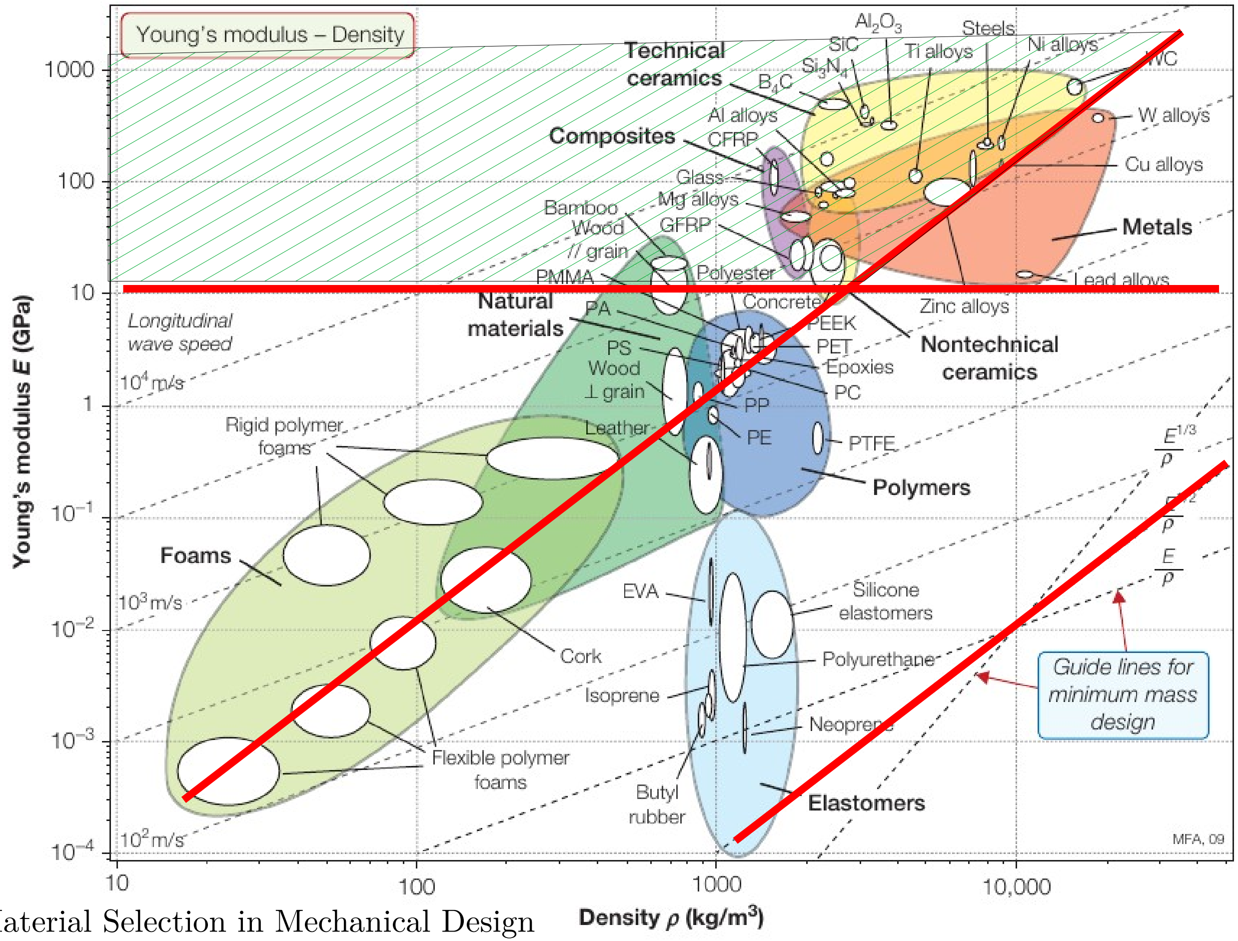
Functional parameters **G**eometric parameters **M**aterial properties

$m \geq f_1(F) f_2(G) f_3(M)$ separable form

To minimize the mass we therefore need to maximize the material index $\dfrac{E^{1/2}}{\rho}$

Material	$\rho\,(\mathrm{kg/m^3})$	E(GPa)	σ_y(MPa)	$E^{1/2}/\rho$
1020 Steel	7850	205	320	58
6061 Al	2700	70	120	98
Ti-6Al-4V	4400	115	950	77
GFRP	1750	28	300	96

Material Property Chart



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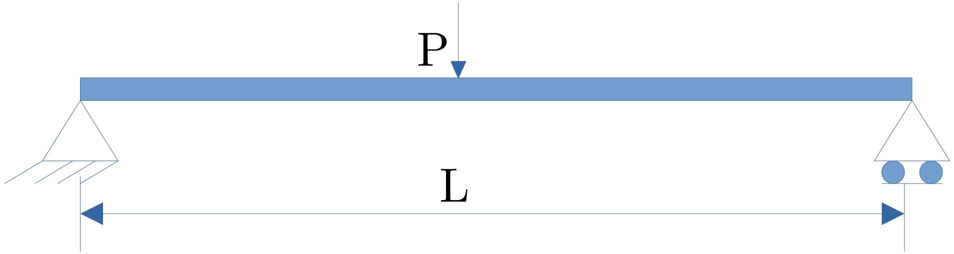
Development of Material Index

- Define the design requirements:
  - Function: What does the component do?
  - Constraints: Essential requirements that must be met: e.g., stiffness, strength, etc.
  - Objective: What is to be maximized or minimized?
  - Free variables: Which are the unconstrained variables of the problem?
- List the constraints and develop an equation for them
- Develop an equation for the objective in terms of the functional requirements, the geometry, and the material properties (objective function).
- Identify the free (unspecified) variables.
- Eliminate the free variables from the constraint equations.
- Group the variables into three groups: functional requirements $f_1(F)$, geometry $f_2(G)$, and material properties $f_3(M)$;
- Read off the material index, expressed as a quantity $f_3(M)$ that optimizes the performance

Example – Single Objective Single Constraint

Choose a material for a simply supported light beam with a square c/s with max stress being less than the failure strength



Constraint: max stress should be at least σ_f^*

Objective: minimize the mass of the beam

Free variable: material and c/s area A

Material	ρ (kg/m³)	E(GPa)	σ_y(MPa)
1020 Steel	7850	205	320
6061 Al	2700	70	120
Ti-6Al-4V	4400	115	950
GFRP	1750	28	300

$$I = \frac{b^4}{12}, \; M_{max} = \frac{PL}{4}$$

$$\sigma = -\frac{My}{I}, \; \sigma_{max} = \frac{3PL}{b^3}$$

Example – Single Objective Single Constraint

Mass $m = \rho A L$

Max stress $\sigma_{max} = \dfrac{3PL}{b^3}$

$$\sigma_{max} \leq \sigma_y \qquad \text{constraint}$$

$$\frac{3PL}{b^3} \leq \sigma_y$$

$$\frac{3PL}{\left(\frac{m}{\rho L}\right)^{3/2}} \leq \sigma_y$$ Substitute for b in terms of mass m

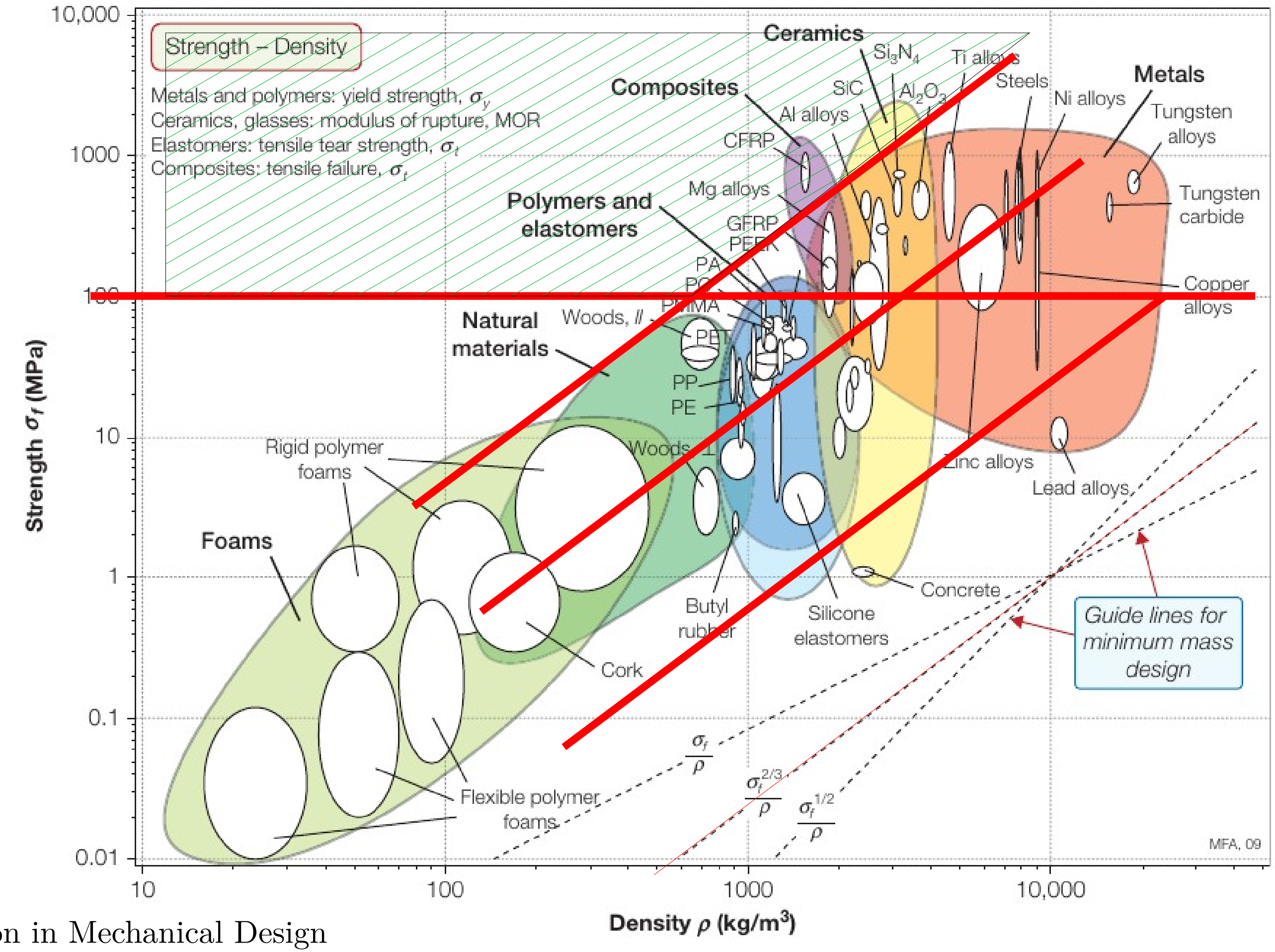
or

$$m \geq \left((3P)^{2/3}\right)\left(L^{5/3}\right)\left(\frac{\rho}{\sigma_y^{2/3}}\right)$$

Material	$\rho\,(\mathrm{kg/m^3})$	E(GPa)	σ_y(MPa)	$\sigma_y^{2/3}/\rho$
1020 Steel	7850	205	320	60
6061 Al	2700	70	120	90
Ti-6Al-4V	4400	115	950	219
GFRP	1750	28	300	256

To minimize the mass we therefore need to maximize the material index $\dfrac{\sigma_y^{2/3}}{\rho}$

Material Property Chart



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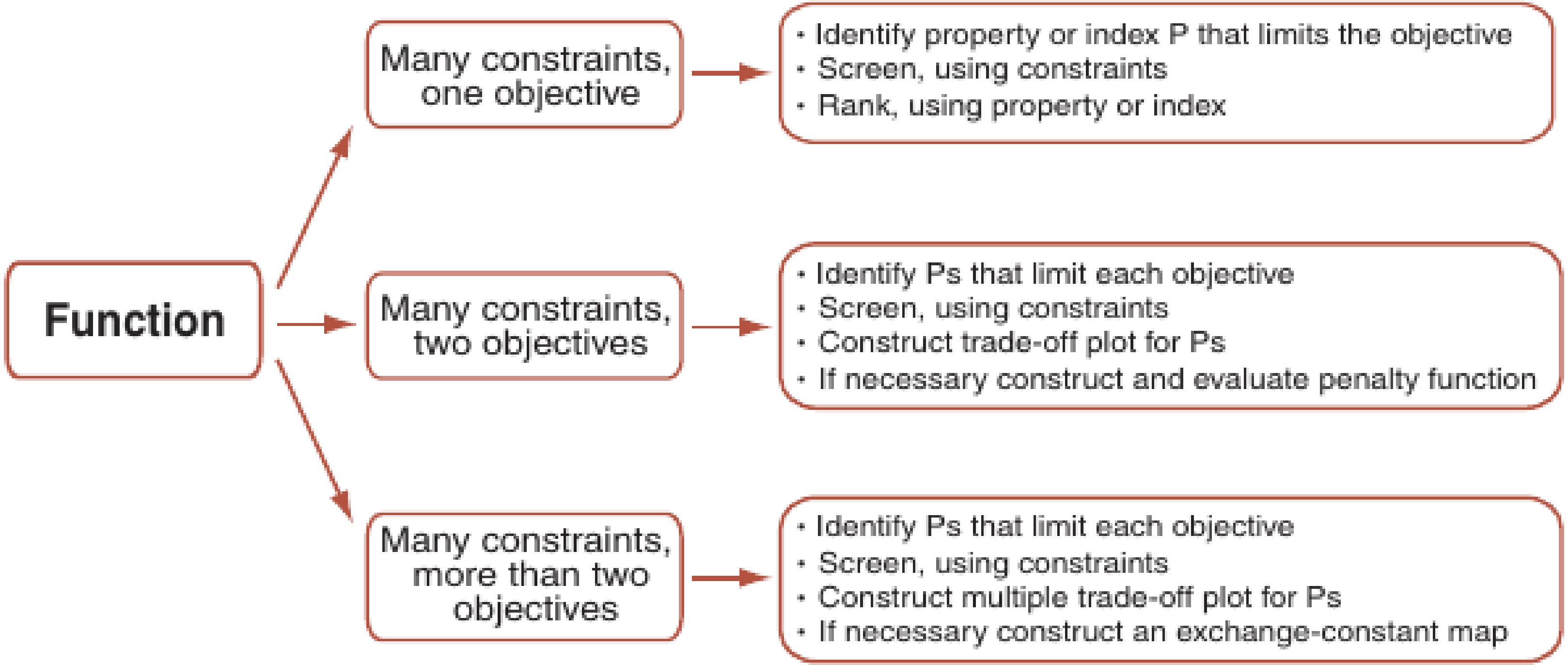
Additional Types of Problems



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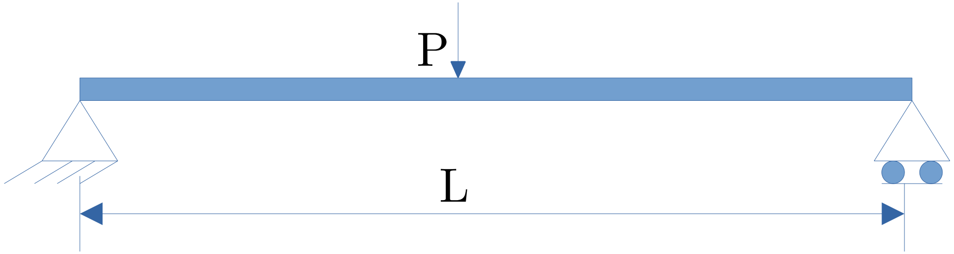
Example – Single Objective Multiple Constraints

Choose a material for a simply supported light beam with a square c/s with max stress being less than the failure strength **and** stiffness being at least S^* . Here L = 1m, P = 100 kN, $S^* = 3\text{x}10^7$ N/m



$$m \geq \left(\frac{1}{2}\sqrt{S^*}\right)\left(L^{5/2}\right)\left(\frac{\rho}{E^{1/2}}\right) \quad \text{stiffness}$$

$$m \geq \left((3P)^{2/3}\right)\left(L^{5/3}\right)\left(\frac{\rho}{\sigma_y^{2/3}}\right) \quad \text{strength}$$

Material	ρ (kg/m^3)	E(GPa)	σ_y(MPa)
1020 Steel	7850	205	320
6061 Al	2700	70	120
Ti-6Al-4V	4400	115	950
GFRP	1750	28	300

Example – Single Objective Multiple Constraints

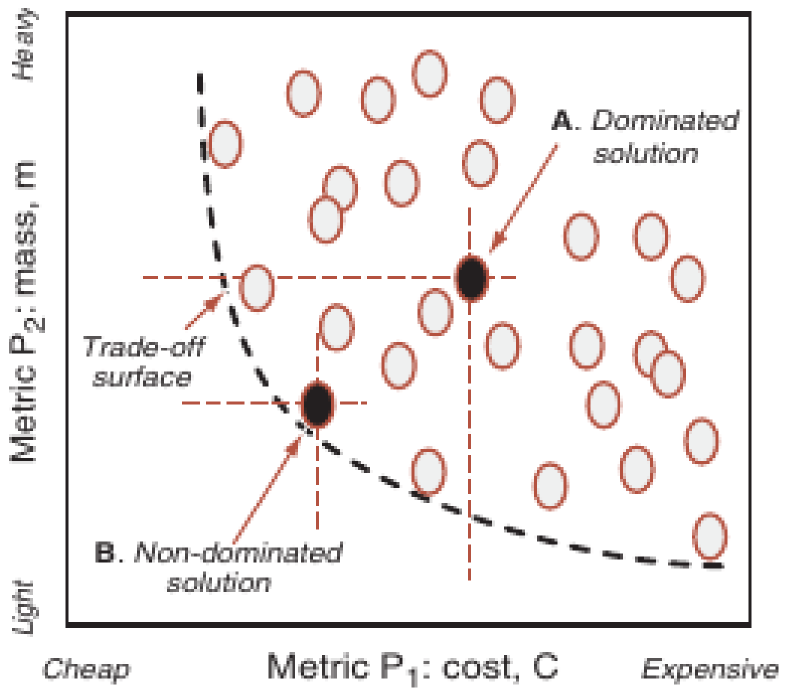
Material	ρ (kg/m^3)	E(GPa)	σ_y(MPa)	m1 [S*](kg)	m2 [σ_y](kg)	max(m1,m2)
1020 Steel	7850	205	320	47	75	75
6061 Al	2700	70	120	28	50	50
Ti-6Al-4V	4400	115	950	36	20	36
GFRP	1750	28	300	29	18	**29**

min(max(m1,m2))=29

Example of a min-max problem

Multi-Objective Problems

Problem: Identify a material which minimizes both mass (performance metric P1) and cost (performance metric P2) while also meeting a set of constraints



- Each bubble represents a material – does not violate any constraints
- The materials that minimize P1 do not minimize P2 and vice versa
- Materials such as that at A, are far from optimal — all the materials in the box attached have lower values of both P1 and P2 – Dominated Solutions
- Materials like those at B have the characteristic that no other materials exists with lower values of both P1 and P2. Non-dominated solutions.

  The line or surface on which the non-dominated solutions lie is called the optimal trade-off surface or Pareto surface
- Different methods exists for solving such projections

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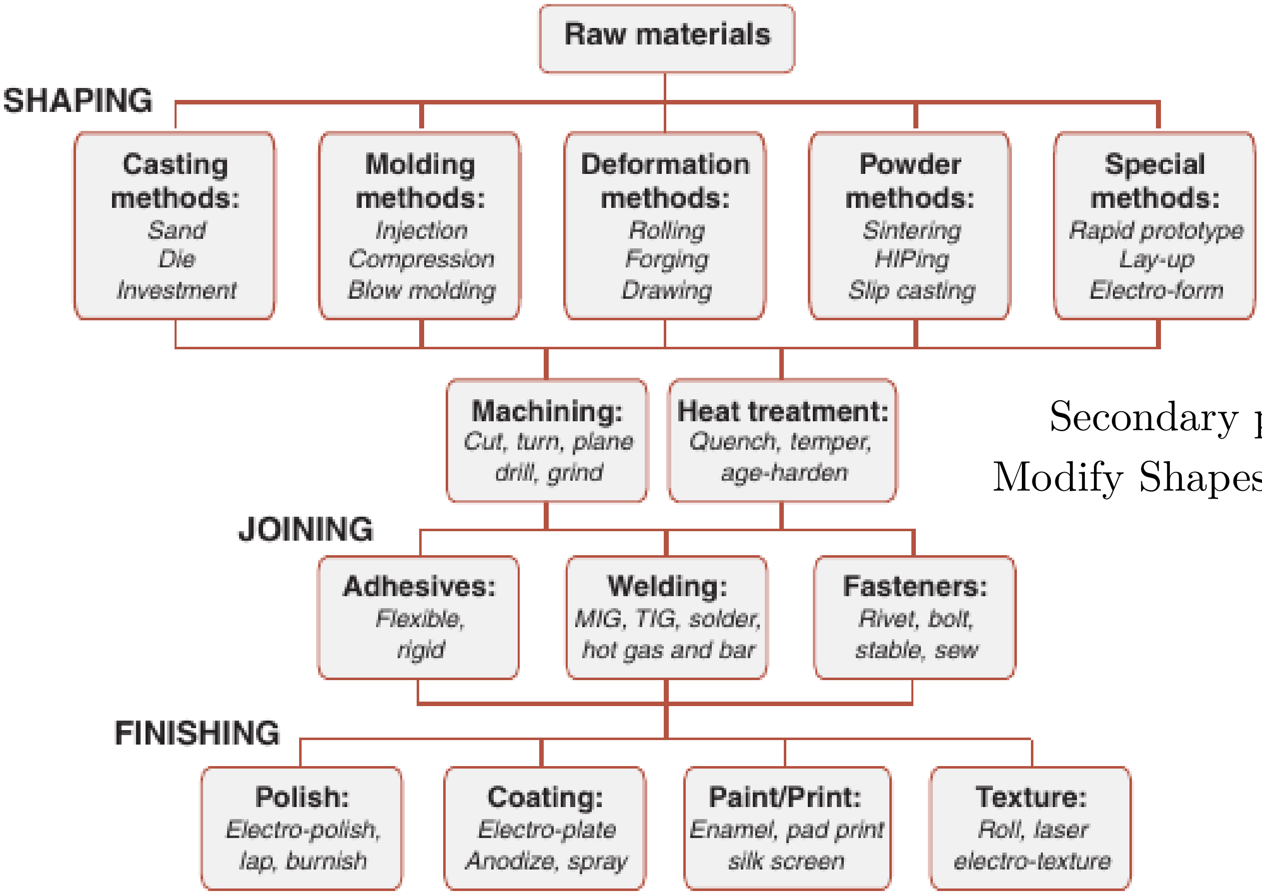
Types of Processes



Primary processes
Create Shapes

Secondary processes
Modify Shapes/Properties

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The Process–Material Matrix

		Metals, ferrous	Metals, non-ferrous	Ceramics	Glasses	Elastomers	Thermoplastics	Thermosets	Polymer foams	Composites
Shaping	Sand casting	●	●							
	Die casting	●	●							
	Investment casting	●	●							
	Low pressure casting		●							
	Forging	●	●							
	Extrusion		●							
	Sheet forming	●	●							
	Powder methods	●	●	●						
	Electro-machining	●	●	●						
	Conventional machining	●	●	●	●	●	●	●	●	
	Injection molding				●	●	●	●	●	
	Blow molding				●		●			
	Compression molding				●	●	●	●		
	Rotational molding					●	●	●	●	
	Thermo-forming					●	●	●		
	Polymer casting					●	●	●	●	
	Resin-transfer molding						●	●	●	●
	Filament winding									●
	Lay-up methods									●
	Vacuum bag									●
Joining	Adhesives	●	●	●	●	●	●	●	●	●
	Welding, metals	●	●							
	Welding, polymers					●	●	●	●	
	Fasteners	●	●	●	●	●	●	●	●	●
Finishing	Precision machining	●	●				●	●		●
	Grinding	●	●	●	●					●
	Lapping	●	●	●	●					●
	Polishing	●	●	●	●		●	●		●

A red dot indicates that the pair are compatible

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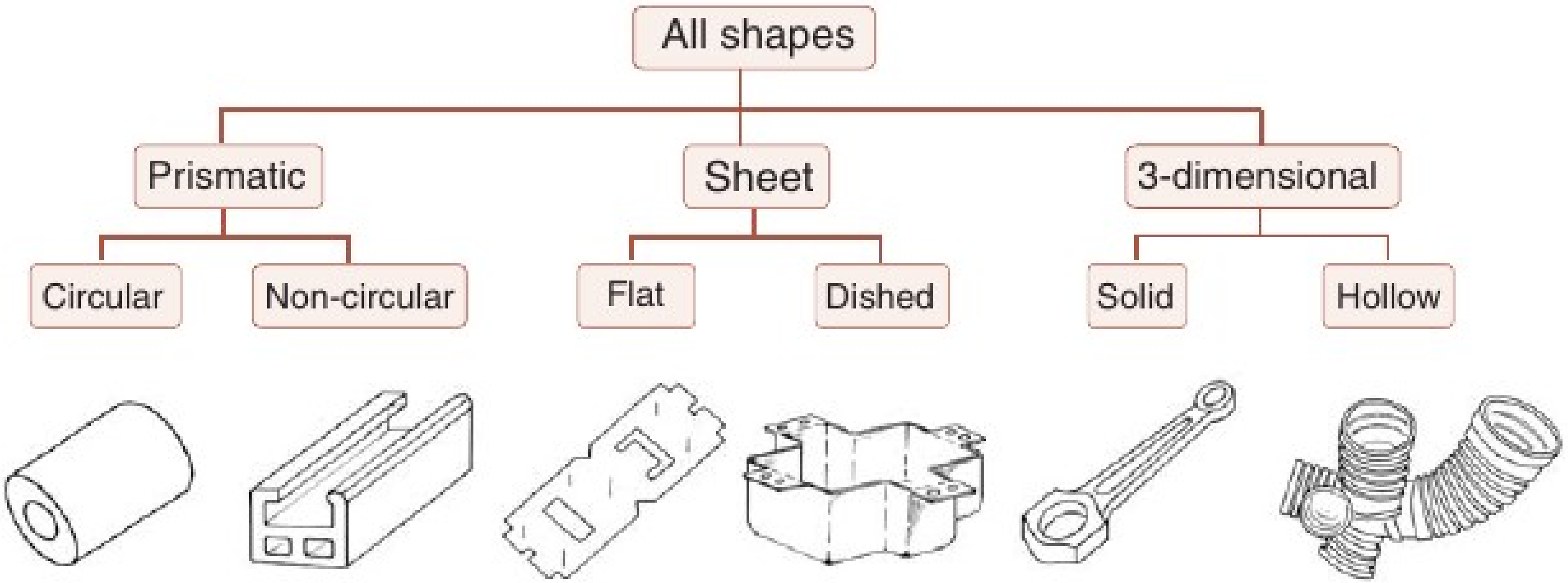
Types of Shapes



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The Process–Shape Matrix

Metal shaping

Ceramic shaping

Polymer shaping

Composite shaping

	Circular prismatic	Non-circular prismatic	Flat sheet	Dished sheet	3-D solid	3-D hollow
Sand casting	●	●			●	●
Die casting	●	●			●	●
Investment casting	●	●			●	●
Low pressure casting	●	●			●	●
Forging	●	●			●	
Extrusion	●	●				
Sheet forming	●	●	●	●		
Powder methods	●	●			●	●
Electro-machining	●	●	●		●	●
Conventional machining	●	●	●	●	●	●
Injection molding	●	●			●	●
Blow molding				●		●
Compression molding			●	●	●	
Rotational molding				●		●
Thermo-forming				●		
Polymer casting	●	●			●	●
Resin-transfer molding	●	●	●	●	●	●
Filament winding	●	●		●		●
Lay-up methods			●	●	●	
Vacuum bag			●	●		

A red dot indicates that the pair are compatible

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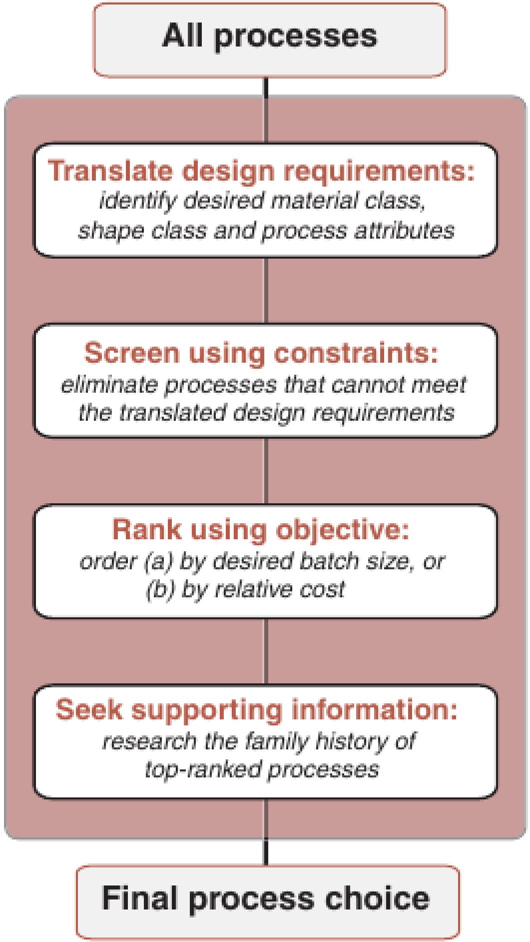
Procedure for Process Selection



Procedure is identical to the material selection procedure

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