Composite Materials

Introduction

Outline

- *Composite Materials course gives an ability to identify the properties of reinforcements and matrix materials used in composites, as well as types and design of composite materials, most common manufacturing techniques, advantages and limitations, properties of composite materials and typical application area*

Content

Course Content:	
1. Week	Introduction to composite materials. General properties of ceramic, metal and polymer materials. Definitions (matrix, reinforcement, interface, etc.). Classification of composite materials.
2. Week	Introduction to reinforcements (particles, fibers, whiskers, etc.). Properties of reinforcements.
3. Week	Reinforcement-matrix interactions (particles, fibers, whiskers, etc.). Fabrication of reinforcements.
4. Week	Ceramic matrix composites. Processing, properties and applications.
5. Week	Ceramic matrix composites. Processing, properties and applications.
6. Week	I. Midterm Exam
7. Week	Metal matrix composites. Processing, properties and applications.
8. Week	Metal matrix composites. Processing, properties and applications.
9. Week	Polymer matrix composites. Processing, properties and applications.
10. Week	Polymer matrix composites. Processing, properties and applications.
11. Week	II. Midterm Exam
12. Week	Mechanical properties of composite materials.
13. Week	Mechanical properties of composite materials.
14. Week	Characterisation of composite materials via destructive and non-destructive techniques. Future trends in composite materials research, production and applications.

References

- *Krishnan K. Chawla, "Composite Materials Science and Engineering", Springer, 2001.*
- *Matthews, F.L. and R.D. Rawlings, 1999, Composite Materials: Engineering and Science, Woodhead Publishing.*
- *Handbook of Composites, American Society of Metals, 1990.*
- *Derek Hull, "Introduction to Composite Materials", Cambridge University Press, 1988.*
- *Brent Strong, "Principles of Composites Manufacturing", Society of Manufacturing Engineers, 1989*

Basic Definitions

- *What is a composite?*

A mixture or hybrid that contains two or more chemically distinct and physically separable materials

One material is continuous and is termed the matrix, while the second, usually discontinuous phase, is the dispersed phase

The dispersed phase (or phases) is imbedded in the matrix in a continuous or discontinuous form. It is usually stronger than the matrix, therefore it is sometimes called reinforcing phase. It can be of the three basic material classes

Basic Definitions

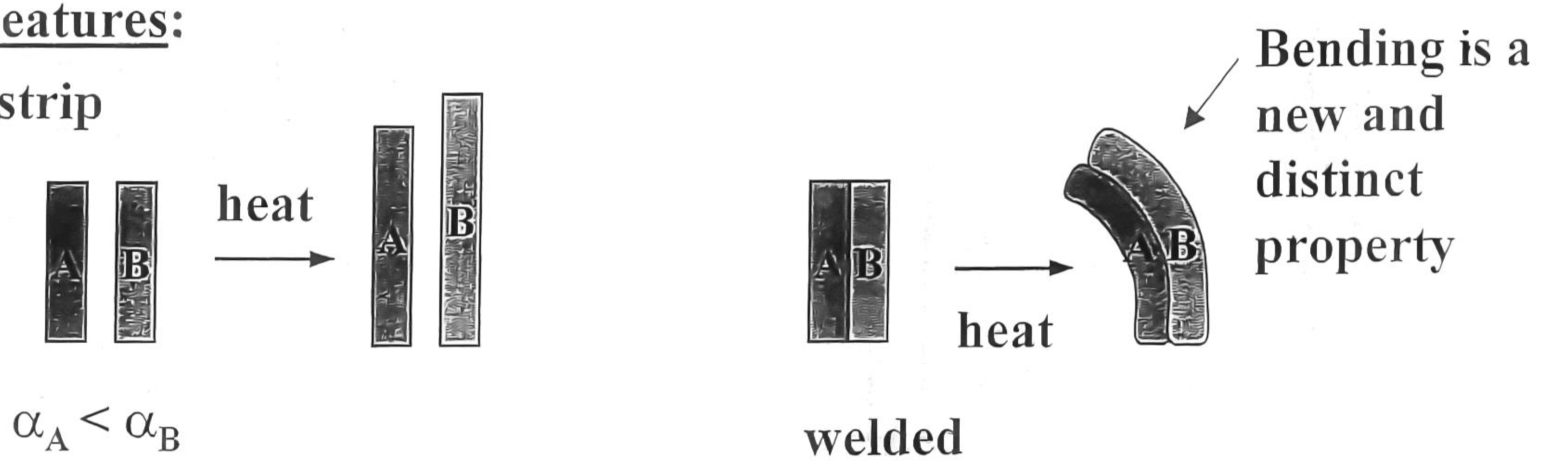
- *What is a composite?*

Separate materials are mixed in a controlled way to achieve optimum properties

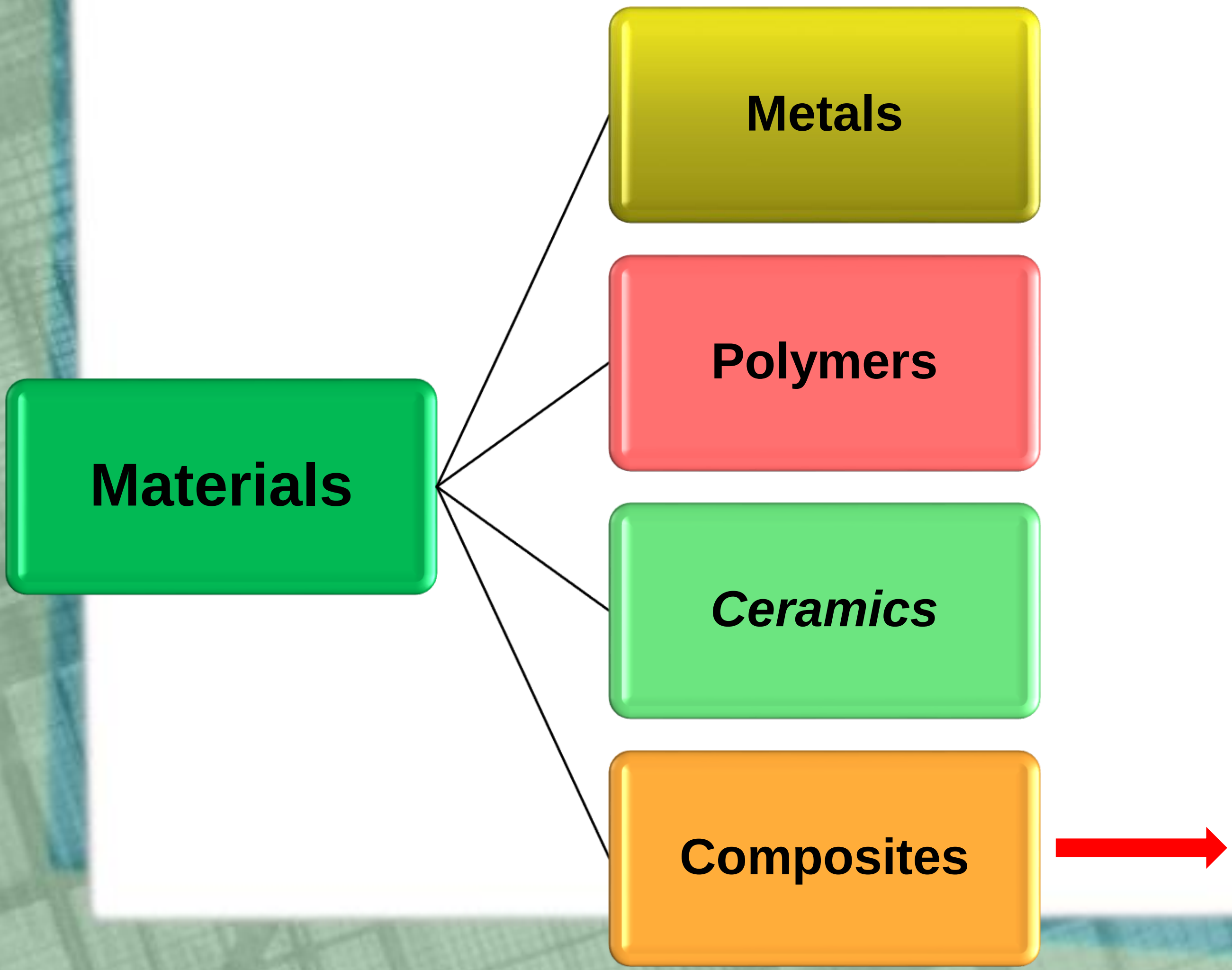
The properties are superior and unique in some aspects to the properties of the individual components

Synergic Features:

Ex: Bimetallic strip



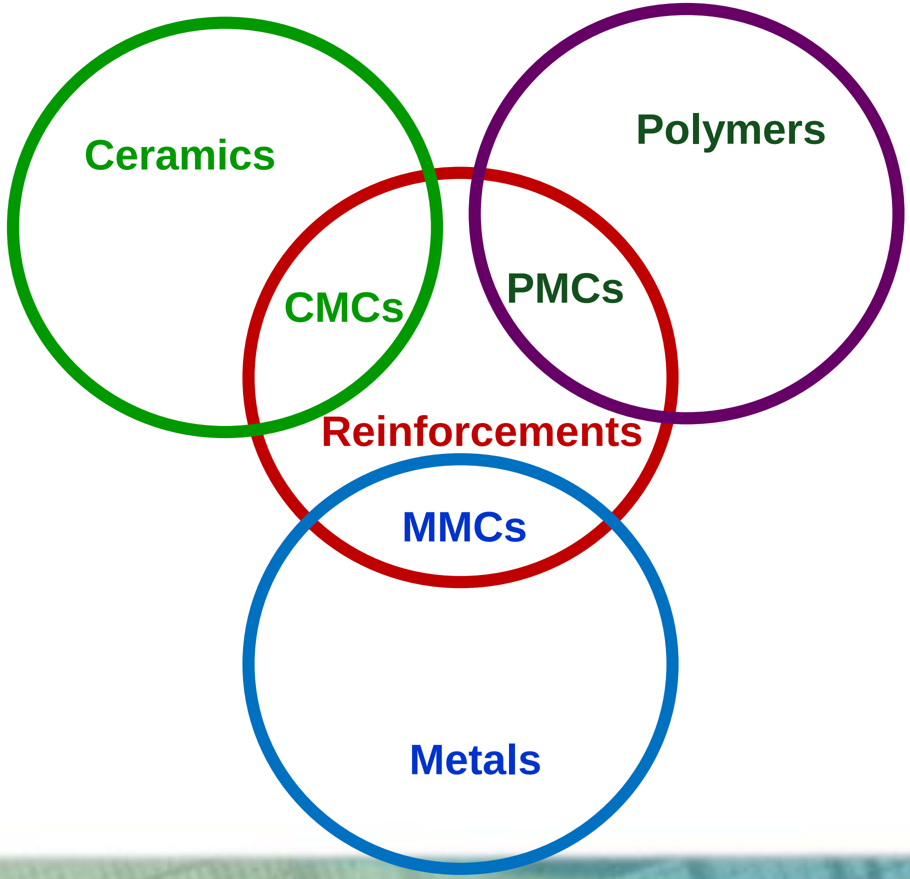
General relation between the matrix and reinforcement materials



With technological progress, natural materials become insufficient to meet increasing demands on product capabilities and functions.

Basic Definitions

- *What are the classes and types of composites?*



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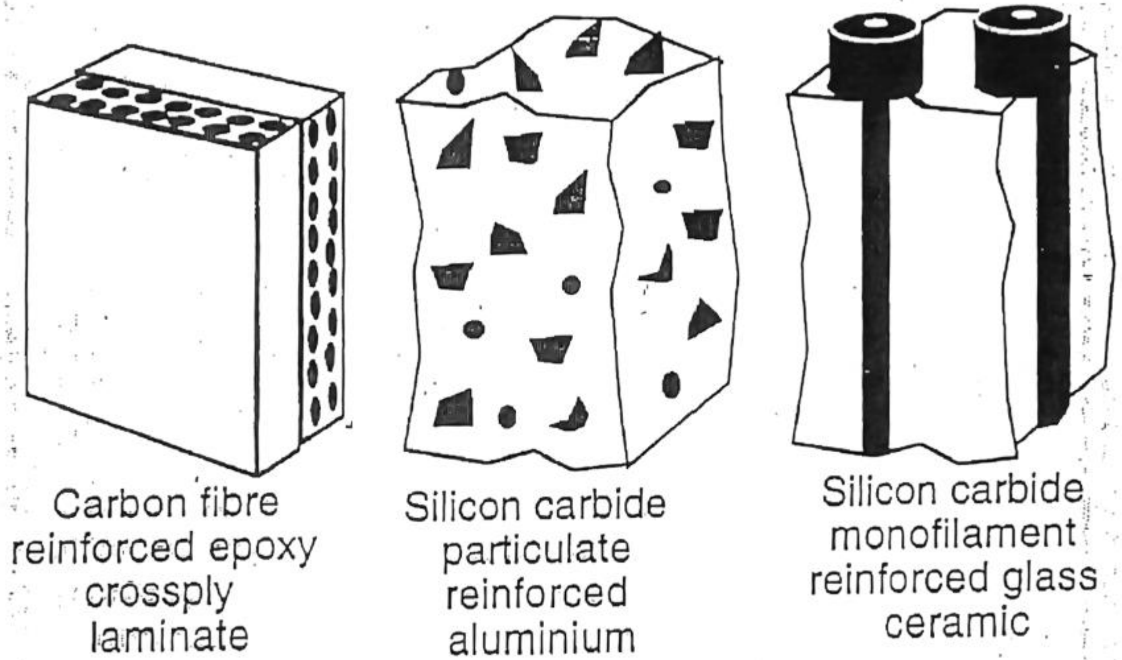


Schematic depiction of representative polymer, metal and ceramic matrix composites.

Basic Definitions

- *What is the function of the matrix phase?*

Provides the bulk form of the part or product

Holds the imbedded phase in place

Shares the load with the secondary phase

Protect the reinforcements from surface damage due to abrasion or chemical effect

Bonding strength between reinforcement and matrix is important (interphase)

Basic Definitions

- *What is the motivation of manufacturing composites?*

To overcome current limits of monolithic of conventional materials

CERAMICS
- **Hard, corrosion and wear resistant**
- **BUT BRITTLE**

METALS
- **Soft, conductive, high fracture toughnes, ductile**
- **HEAVY, low temperature use**

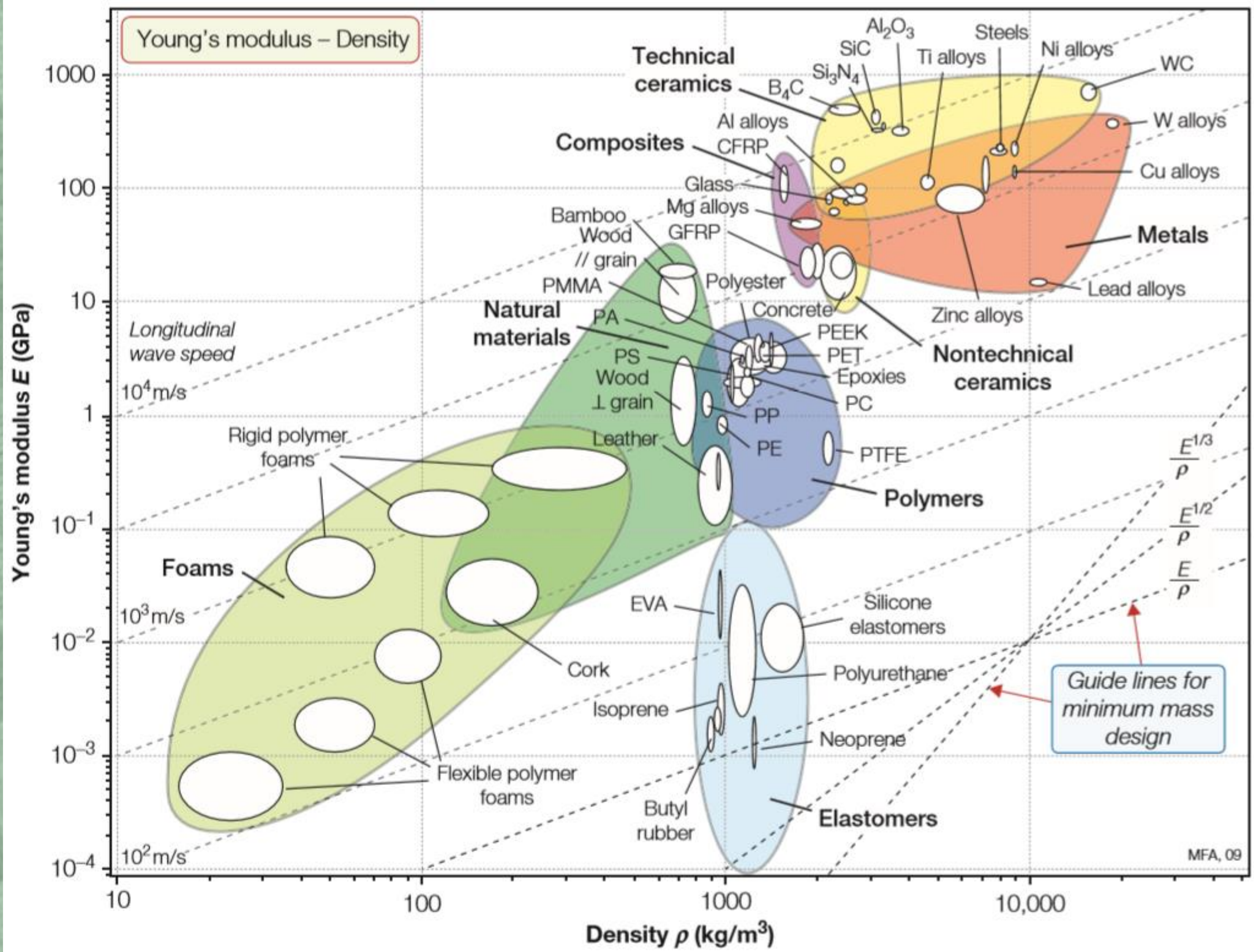
GLASSES
- **Non-crystalline solid, hard,**
- **Brittle, vulnerable to stress concentration**

POLYMERS
- **Easy to shape**
- **Low modulus, low temperature use**

A comparison of the properties of conventional materials

	Ceramic	Metal	Polymer
Hardness	↑	↓	↓
Elastic modulus	↑	↑	↓
High temperature strength	↑	↓	↓
Thermal expansion	↓	↑	↑
Ductility	↓	↑	↑
Corrosion resistance	↑	↓	↓
Resistance to wear	↑	↓	↓
Electrical conductivity	↑↓	↑	↓
Density	↓	↑	↓
Thermal conductivity	↑↓	↑	↓

↑ Tendency to high values — ↓ Tendency to low values



Young's modulus – Density
Technical ceramics
Composites
Natural materials
Foams
Polymers
Elastomers
Metals
Nontechnical ceramics
Al2O3
SiC
Si3N4
B4C
Steels
Ti alloys
Ni alloys
WC
W alloys
Cu alloys
Al alloys
CFRP
Glass
Mg alloys
GFRP
Bamboo
Wood // grain
PMMA
Polyester
Concrete
Zinc alloys
Lead alloys
PA
PS
PEEK
PET
Epoxies
PC
Wood ⊥ grain
PP
PE
PTFE
Leather
Rigid polymer foams
Flexible polymer foams
Cork
EVA
Silicone elastomers
Polyurethane
Isoprene
Neoprene
Butyl rubber
Longitudinal wave speed
10^4 m/s
10^3 m/s
10^2 m/s
E^1/3/ρ
E^1/2/ρ
E/ρ
Guide lines for minimum mass design
MFA, 09
Young's modulus E (GPa)
Density ρ (kg/m^3)

Basic Definitions

- *What is the motivation of manufacturing composites?*

*Common driving forces for the use of composite materials include the ability to **save weight**, **increase mechanical properties**, **reduce the number of elements in a component**, **obtain a unique combination of properties**, **increase shaping freedom,** and sometimes **reduce part cost***

Many of these driving forces often offset the higher raw material costs of the composite constituents to produce a commercially viable end product

Basic Definitions

- *What are the design considerations for the matrix?*

The main objectives of the matrix material are to transfer stress to other phases and to protect the dispersed phases

*So **stiffness** and **adhesion strength** are important*

In addition,

- *Toughness*
- *Viscosity*
- *End use temperature*
- *Flame retardancy*
- *Cosmetic issues*

General information about composites

- *Combination of 2 or more materials*
- *Each of the materials must be present by more than 5%*
- *There exists interphases in the structure*
- *The properties shown by the composite materials are different from the initial materials*
- *Can be produced by various processing techniques that are unique to the component phases*

General information about composites

- *Polymers (Thermoplastics, thermosets) are the most commonly used matrix materials due to their easy processability, easy dispersion of the second phase and poor mechanical properties*
- *Fibers are the most commonly used form of dispersed reinforcing phase (long, short, continuous, fabric, preform)*
  - *Glass (95% of all)*
  - *Carbon*
  - *Aramid*
  - *Polymer*
  - *Natural (plant fibers)*

Comparison of properties for different classes of materials

Table 1.1 *Overview of properties exhibited by different classes of material*

Type of material (example)	Density ρ ($Mg\ m^{-3}$)	Young's modulus E (GPa)	Tensile strength σ (MPa)	Fracture toughness K_c (MPa $\sqrt{m}$)	Thermal conductivity K ($W\ m^{-1}\ K^{-1}$)	Thermal expansivity α ($10^{-6}\ K^{-1}$)
Thermosetting resin (epoxy)	1.25	3.5	50	0.5	0.3	60
Engineering thermoplastic (nylon)	1.1	2.5	80	4	0.2	80
Rubber (polyurethane)	1.2	0.01	20	0.1	0.2	200
Metal (mild steel)	7.8	208	400	140	60	17
Construction ceramic (concrete)	2.4	40	20	0.2	2	12
Engineering ceramic (alumina)	3.9	380	500	4	25	8
Wood (load // grain)	0.6	16	80	6	0.5	3
(spruce) (load ⊥ grain)	0.6	1	2	0.5	0.3	10
General PMC (in-plane) (chopped strand mat)	1.8	20	300	40	8	20
Adv. PMC (load // fibres)	1.6	200	1500	40	200	0
(APC-2) (load ⊥ fibres)	1.6	3	50	5	40	30
MMC (Al–20%SiC_p)	2.8	90	500	15	140	18

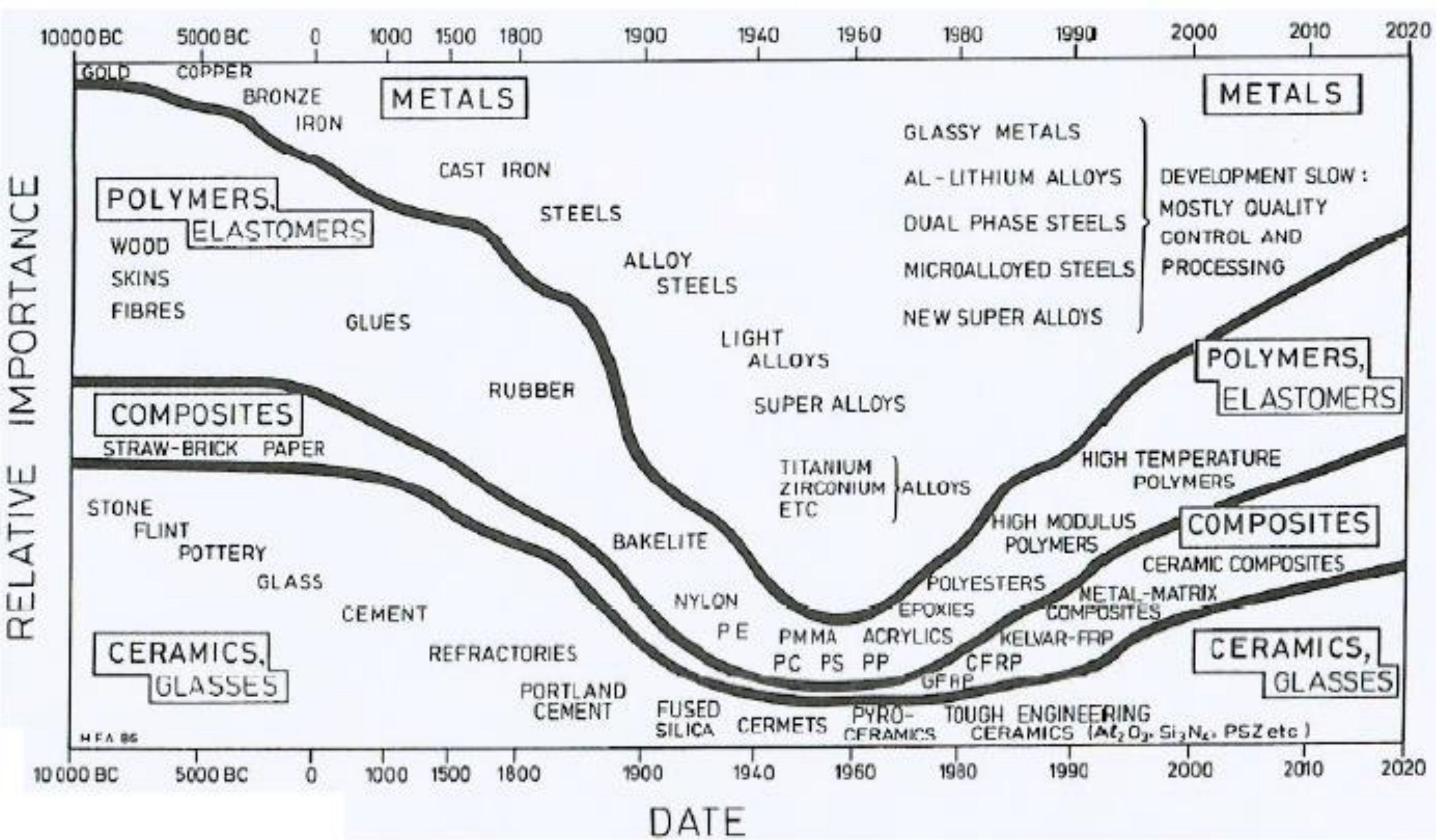
History

- *Composites are not new materials*
- *Perhaps the first important engineering structural composite was the straw-reinforced, sun-dried mud brick — adobe*
- *Laminated structures such as bows have been used since prehistoric times.*
- *In the early 1900s doped fabric was employed in early aircraft surfaces.*
- *Reinforced phenolics were developed in the 1930s and glass-reinforced plastics in the 1940s.*
- *More recently, emphasis turned to reinforcements, with graphitic and boron-based fibers developed in the 1960s.*
- *High-performance aramids, such as Kevlar™, were developed in the 1970s. This and the previous decade have seen new developments in both fiber and matrix with lightweight aerospace MMCs and high-temperature CMCs showing major advances.*

History

- *The ancient Egyptians manufactured composites. Adobe bricks are a good example.*

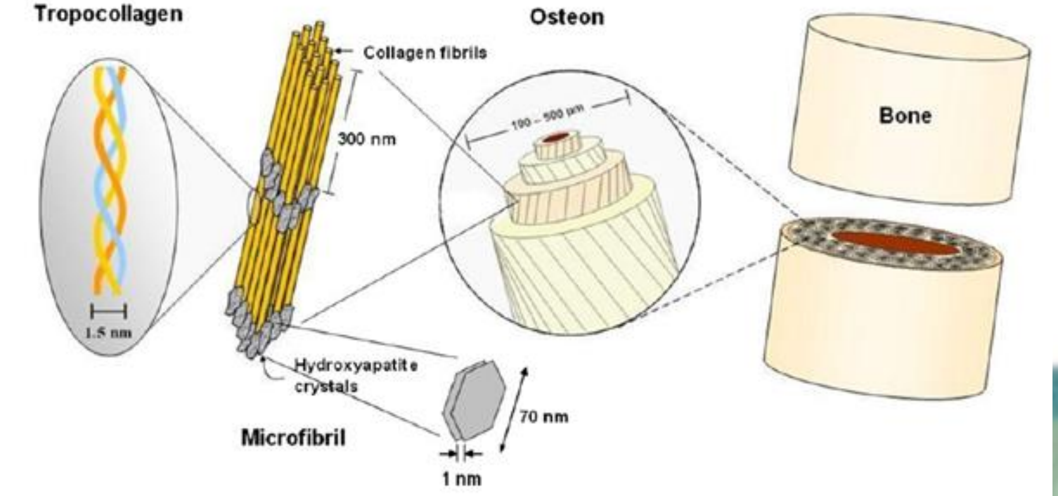
- *The combination of mud and straw forms a composite that is stronger than either the mud or the straw by itself.*



Michael Ashby circa 1980

Natural Composites

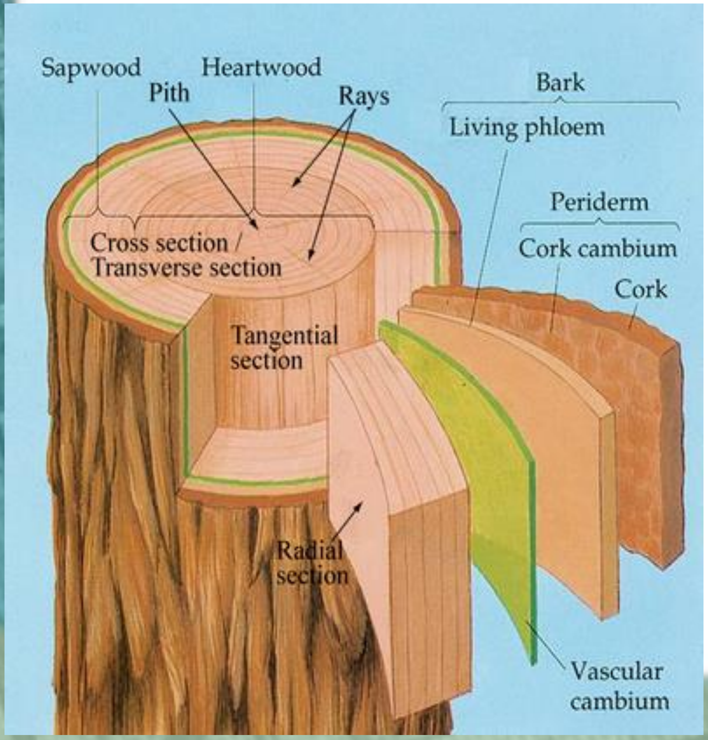
- *Many natural materials are composites*
- *Wood, grasses, bones, fingernails, muscles, bee hives, bird nests, deer antlers, etc.*
- *Wood: strong & stiff cellulose fibers in softer lignin (surrounds the fibers).*
- *Bone: strong but soft collegen (protein) within hard but brittle apatite (mineral).*



Natural Composites

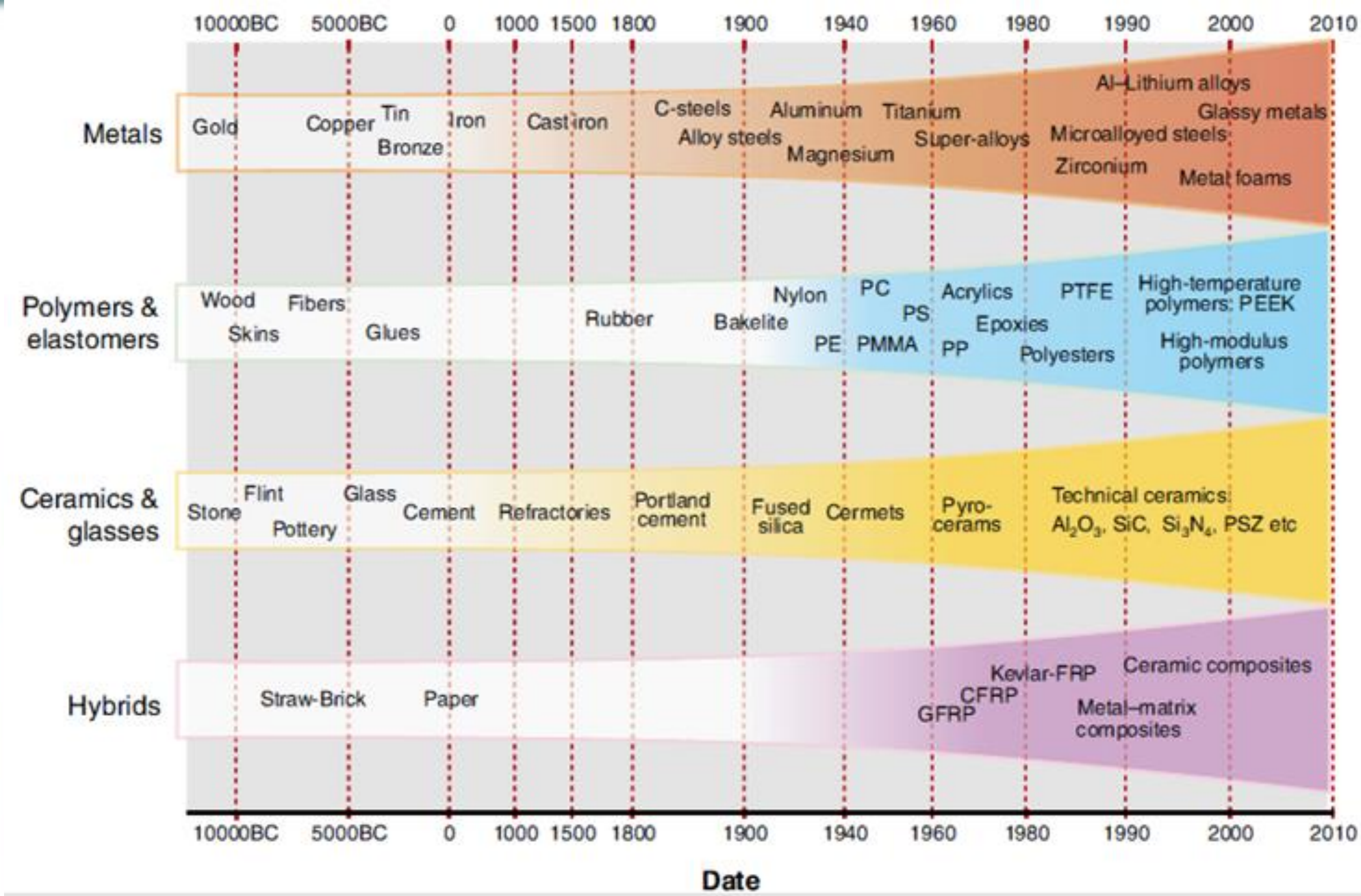
- *Wood (a natural composite as distinguished from a synthesized composite). This is one of the oldest and the most widely used structural material. It is a composite of strong and flexible cellulose fibers (linear polymer) surrounded and held together by a matrix of lignin and other polymers.*

Wood has extreme anisotropy because 90 to 95% of all the cells are elongated and vertical (i.e. aligned parallel to the tree trunk). The remaining 5 to 10% of cells are arranged in radial directions, with no cells at all aligned tangentially. Wood is ten times stronger in the axial direction than in the radial or tangential directions.



A cut-through of a tree trunk

Bamboo is a very efficient wood composite structure. The components are cellulose and lignin, as in all other wood, however bamboo is hollow. This results in a very light yet stiff structure. Composite fishing poles and golf club shafts copy this natural design.



The materials of pre-history, on the left, all occur naturally; the challenge for the engineers of that era was one of shaping them. The development of thermochemistry and (later) of polymer chemistry enabled man-made materials, shown in the colored zones.

Advantages of Composites

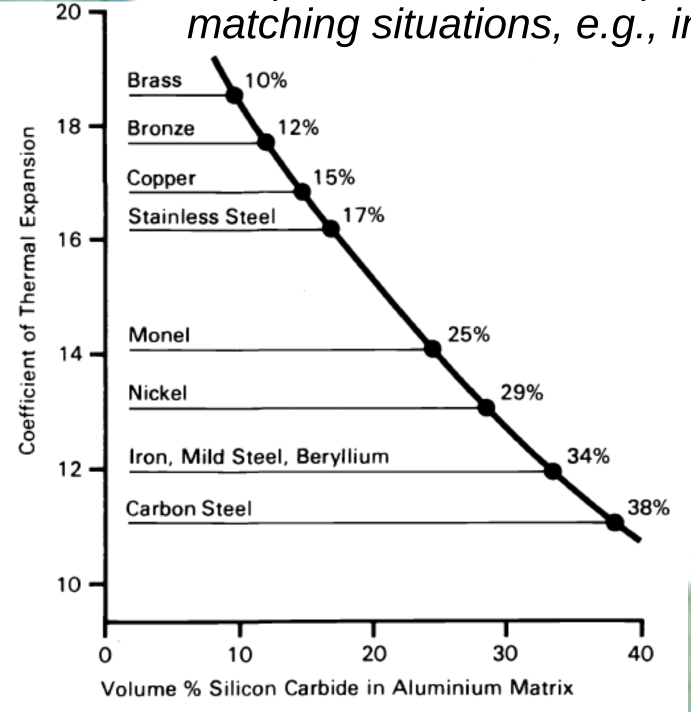
- *Unique combination of properties*

For example, tungsten wire is very stiff (405 GPa) but very dense (19.3 Tonnes/m3). A combination of graphite fibre in epoxy resin is nearly as stiff (306 GPa) but with a density of only 1.5 Tonnes/m3. The carbon fibre itself is much stiffer than the tungsten; values up to 1000GPa at a density of 2.6 onnes/m3 are possible.

Advantages of Composites

- *Properties can be controlled in a wide range*

Figure given below shows the variation of coefficient of expansion with volume fraction for a composite consisting of aluminium containing silicon carbide particles. It is seen that matching the coefficient of thermal expansion with that of other materials is easily obtained. Similar wide range of properties is important in, for example, acoustic wave devices and in many other matching situations, e.g., in prosthetic devices.

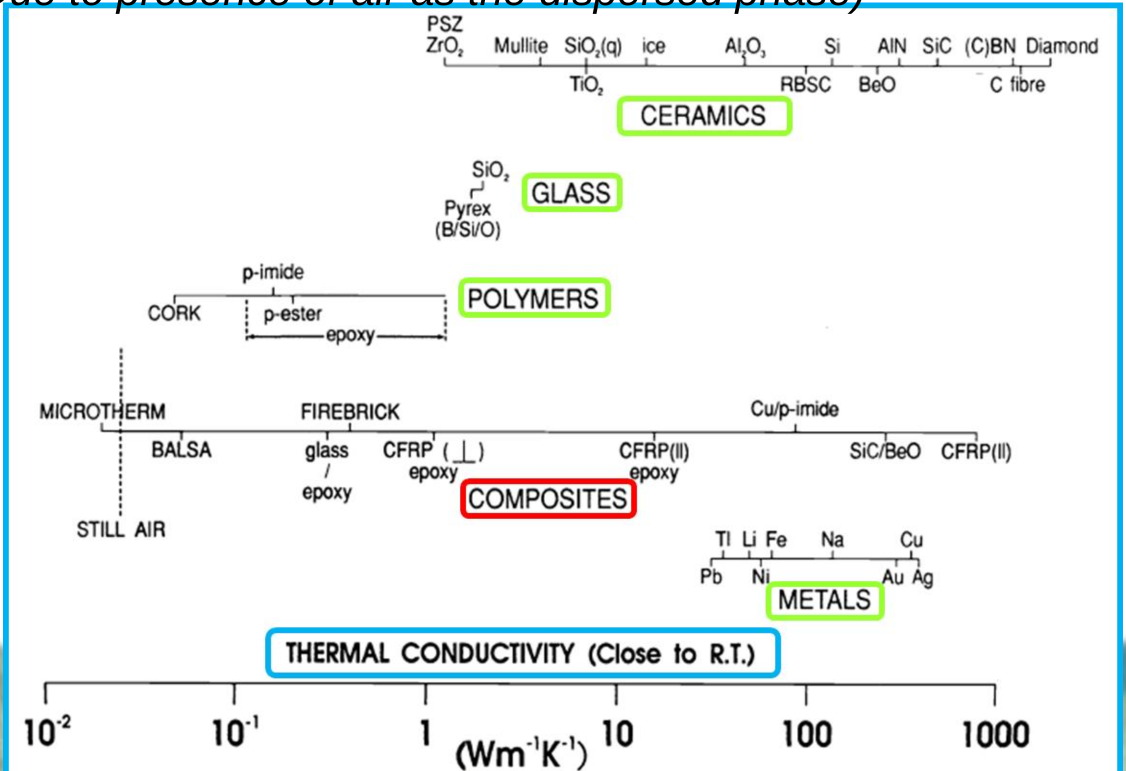


Ordinate values x $10^{-6}K^{-1}$

Advantages of Composites

- *Composites can sometimes attain a value of a given physical property not attainable by either of the two components alone*

Thermal conductivity of various materials are given below and it is quite clear there that composites can attain a lower thermal conductivity than that of others. (Due to presence of air as the dispersed phase)



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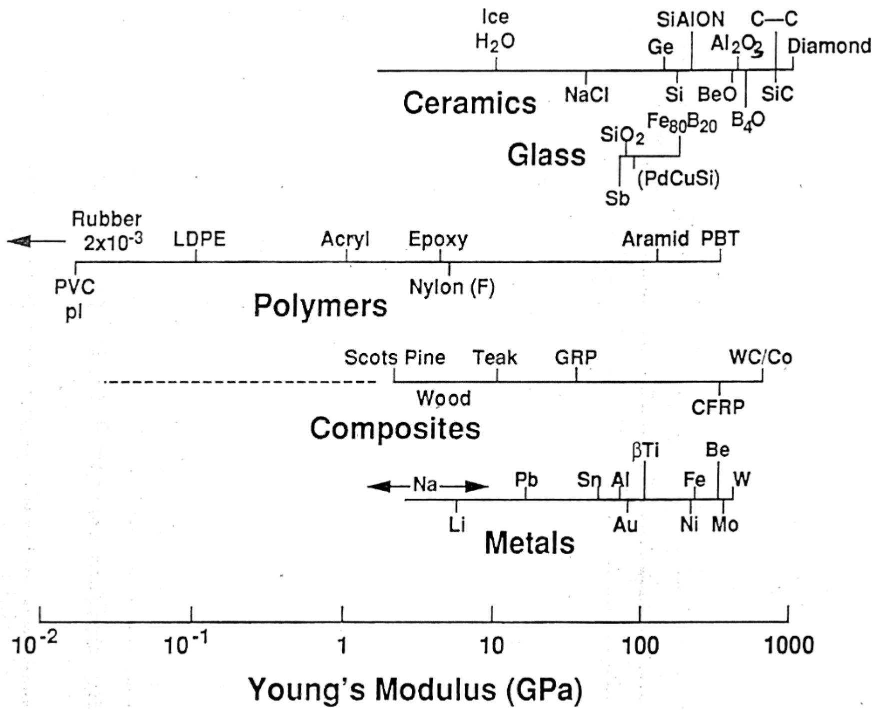
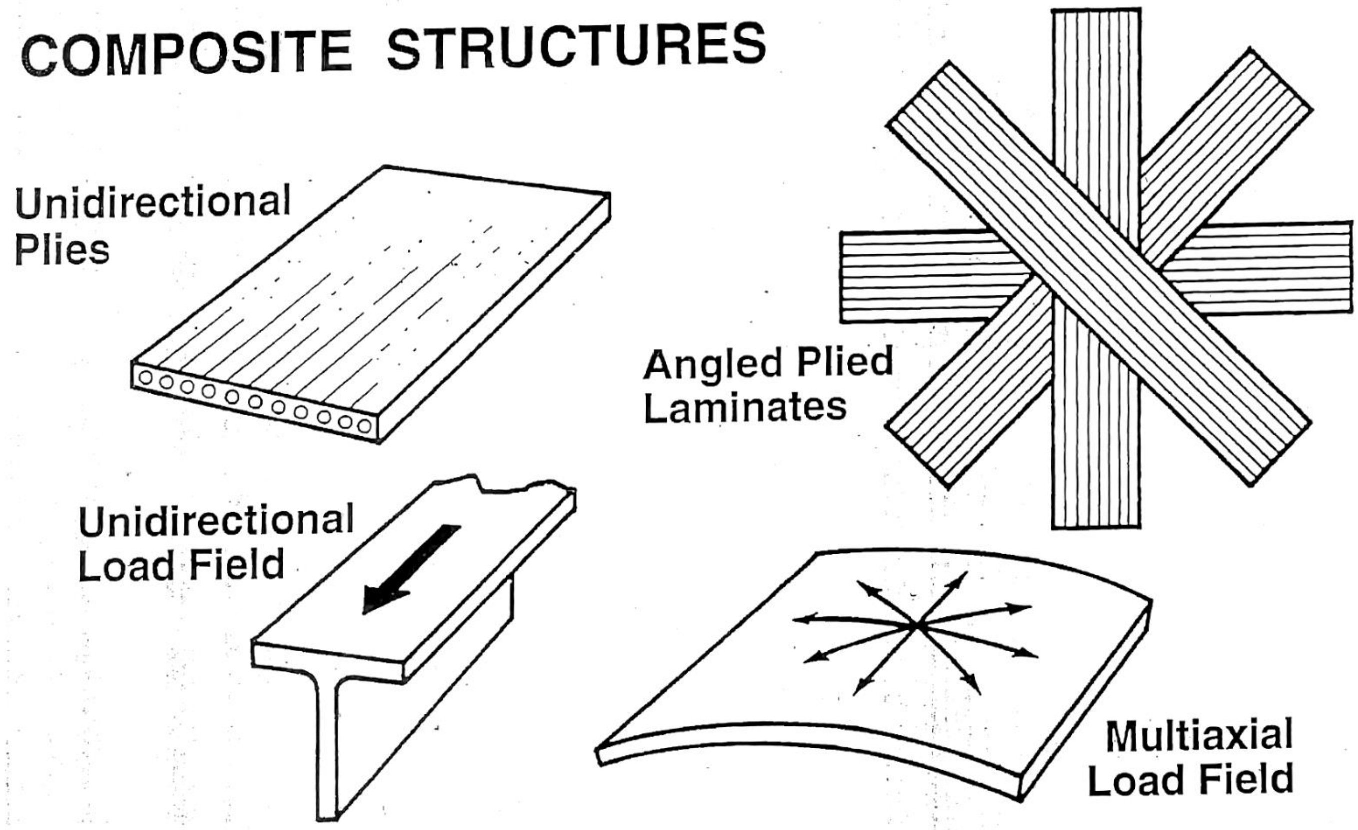


Advantages of Composites

- *Low weight, high specific properties (many natural, and biological materials are composites)*
- *Use of extremely high property (strength and modulus) constituents*
- *Design flexibility: The "rule-of-mixtures" - an additional design degree of freedom*
- *Synergistic effects: Role of the interface, of heterogeneity / anisotropy / hierarchy*
- *Anisotropy: property directionality*
- *Heterogeneity: chemical variability*

Anisotropic structure of composites



Disadvantages of Composites

- *Properties of many important composites are anisotropic - the properties differ depending on the direction in which they are measured – this may be an advantage or a disadvantage*
- *Many of the polymer-based composites are subject to attack by chemicals or solvents, just as the polymers themselves are susceptible to attack*
- *Composite materials are generally expensive*
- *Manufacturing methods for shaping composite materials are often slow and costly*
- *Composites are more brittle than wrought metals and thus are more easily damaged.*
- *Matrix is weak, therefore, low toughness*
- *Difficult to attach*

Disadvantages of Composites

- *Repair, reuse and disposal may be difficult because*

Materials require refrigerated transport and storage and have limited shelf life.

Hot curing is necessary in many cases requiring special tooling.

Hot or cold curing takes time.

Analysis is difficult.

Matrix is subject to environmental degradation

Manufacturing of Composites

- *The primary barrier to the use of composite materials is their high initial costs in some cases, as compared to traditional materials. Regardless of how effective the material will be over its life cycle, industry considers high upfront costs, particularly when the life-cycle cost is relatively uncertain.*

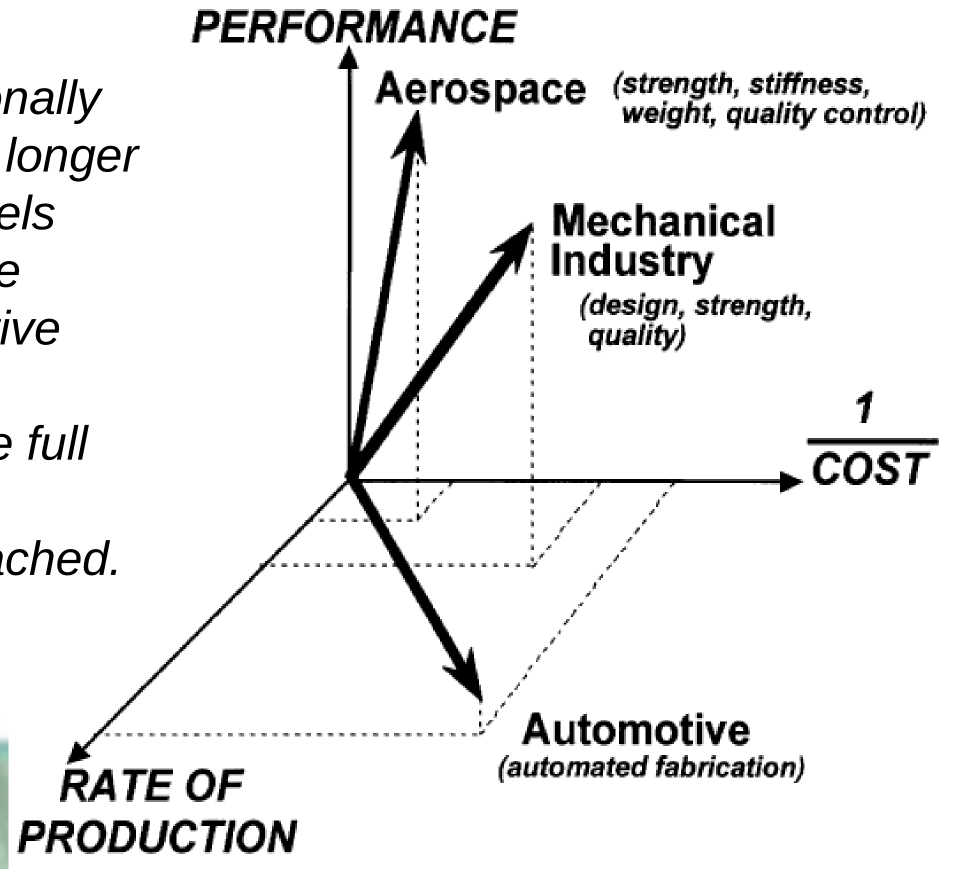
- *In general, the cost of processing composites is high, especially in the hand lay-up process. Here, raw material costs represent a small fraction of the total cost of a finished product. There is already evidence of work moving to Asia, Mexico and Turkey for the cases where labor costs are a significant portion of the total product costs.*

- *The recycling of composite materials presents a problem when penetrating a high-volume market such as the automotive industry, where volume production is in the millions of parts per year. With the new government regulations and environmental awareness, the use of composites has become a concern and poses a big challenge for recycling.*

Manufacturing of Composites

- *The criteria on which composite materials are selected for a particular application are naturally dependent on the industrial sector for which they are intended.*

For example, aerospace has traditionally been driven by performance, where longer cycle times and increased scrap levels were tolerated, whereas high volume applications, typified by the automotive industry, require rapid and highly automated techniques but where the full potential of composites in terms of mechanical properties is seldom reached.

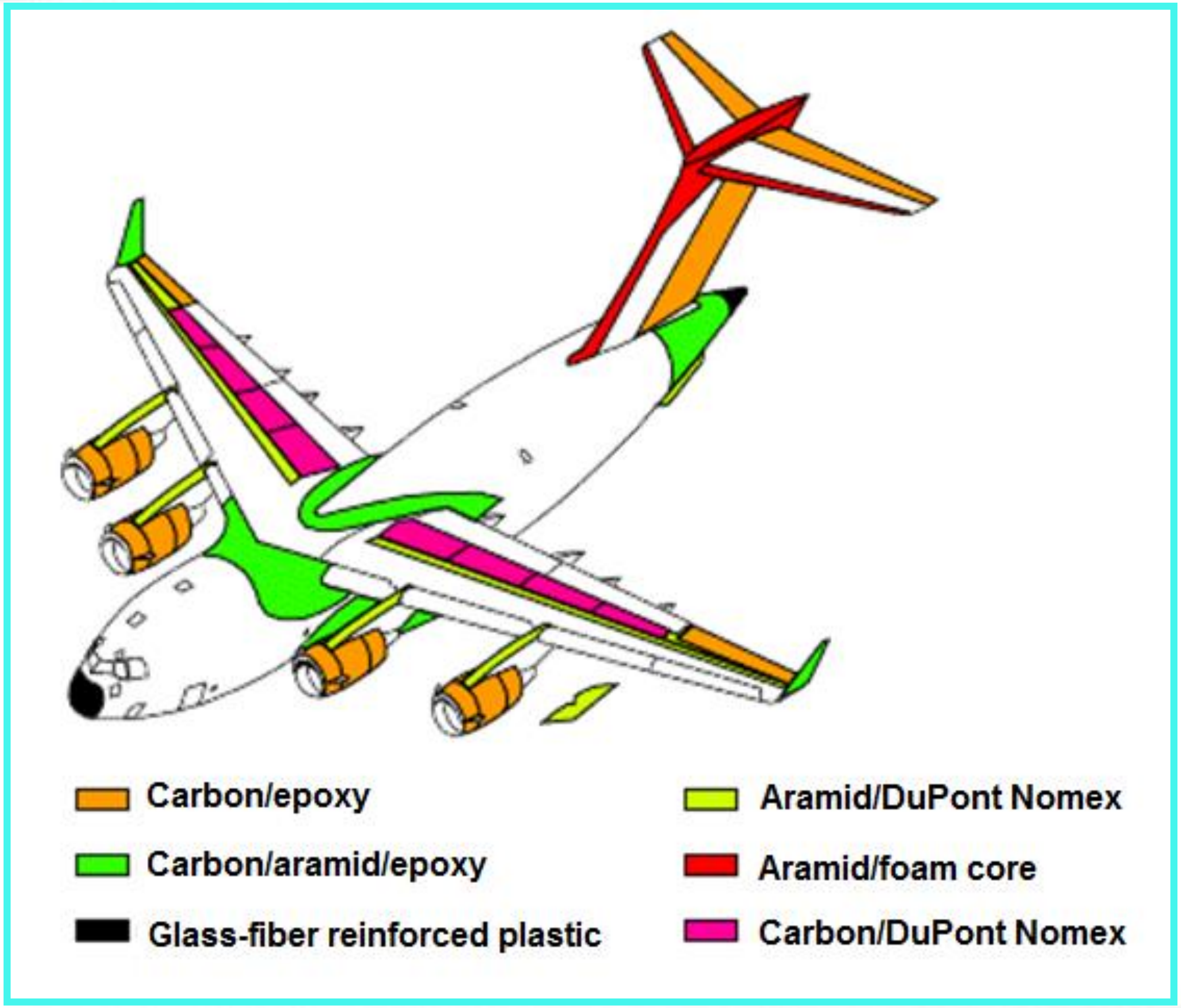


Applications of Composites

- *Composite materials offer a diverse range of properties suited to an equally wide range of applications, offering the design engineer a wide range of opportunities for many different end uses.*
- *Applications vary significantly in size, complexity, loading, operating temperature, surface quality, suitable production volumes, and added value.*
- *The expanding choice of raw materials, in terms of reinforcement type (concentration and fiber architecture) together with matrix material (subsets of both thermoplastic and thermoset polymers), followed by many subsequent final conversion processes gives impressive flexibility.*

Applications of Composites in Aerospace industry

- *A leading role in the development of both composite materials and processing technology has been taken by the aerospace industry.*
- *The high specific stiffness and strength of the reinforcements offered the potential for reduced fuel consumption and increased range with passenger aircraft and increased performance (range, turn rates, stealth) for military aircraft.*
- *The ability to tailor thermal expansion together with the low material density also made materials attractive for space applications. A substantial research effort was therefore made by the aerospace industrial, governmental, and academic communities to develop this material class.*


Carbon/epoxy
Carbon/aramid/epoxy
Glass-fiber reinforced plastic
Aramid/DuPont Nomex
Aramid/foam core
Carbon/DuPont Nomex

Applications of Composites in Aerospace industry

- *The main driving forces for the aerospace industry are therefore primary weight reduction by using a material with higher specific mechanical properties (mechanical property/density), facilitating secondary weight savings, leading to considerable additional weight reduction.*

- *The strong demand for weight saving in aerospace applications, as well as the lower sensitivity of this industry to production rates and material costs, has led to the development of finely-tuned high-performance processing techniques and materials.*

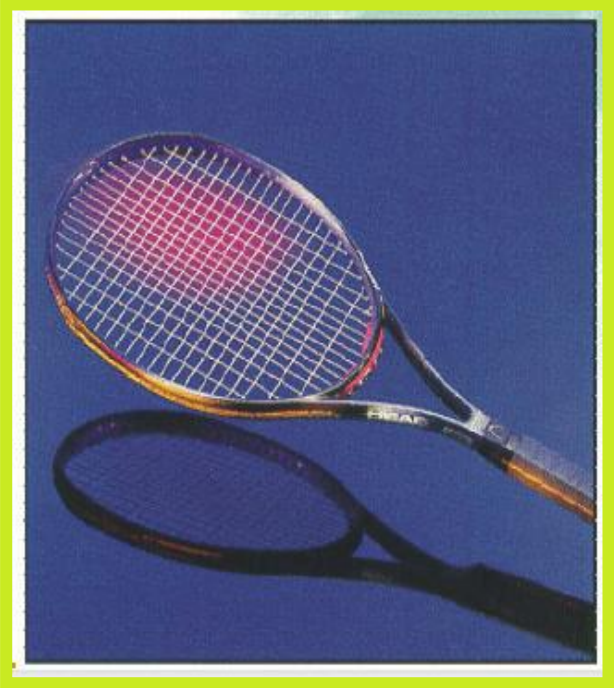
Applications of Composites in Automotive industry

- *The transportation industry represents a potentially large application area for fiber reinforced composites and is driven by a number of interacting driving forces.*
- *The needs of the automotive industry have lead to the development of engineering composites with increased shape complexity*
- *Decreasing system cost must be considered while maximizing quality, functionality, and return on manufacturing investment together with meeting legislative requirements for safety, emissions, and recycling.*

Applications of Composites in Mechanical industry

- *The mechanical industry is currently undertaking large efforts to apply advanced composite materials to specific applications.*
- *Here, the volumes and application demands can generally be considered as lying between those of the aerospace and automotive industries.*
- *Advanced machine elements in high-speed reciprocating or rotational applications necessitate weight reduction in improvement of operation rates and efficiency, as well as in convenience and handling.*
- *Machine elements in high-speed textile and packing machines, pumps, energy conversion equipment, and lightweight hand-machines are some examples of applications in which advanced composite materials are presently being used or evaluated.*

Applications of Composites



Tennis rackets are made from a composite of polyamide fibre in epoxy resin

Applications of Composites

- *Vaulting poles are made using a carbon fibre composite to provide increased strength, flexibility and elasticity. Composite materials are used extensively in the world of sport.*