1 Introduction and Definitions

BASIC DEFINITION

Composite materials can be broadly defined as those containing at least two constituents that can be physically or visibly distinguished. Using this definition, any two-phase material can be considered a composite. In deed, two-phase materials possess many of the mechanical and physical characteristics that are typical of composites. *Engineering composite materials*, are defined more narrowly to emphasize their engineering usefulness. An engineering composite material must meet the three following criteria:

(1) They contain two or more distinct constituents.

(2) They are synthesized in a way that the form, distribution and amount of constituents are controlled in a predetermined way.

(3) They have unique, useful and superior performance that can be predicted from the properties, amounts and arrangements of constituents using principles of mechanics.

All three of these criteria must be met for a material to qualify as a true engineering composite. Table 1.1 lists some well-known two constituent materials that can be tested against these criteria to decide whether they are engineering composites.

Table 1.1 Common materials and their qualification as engineering composites.

Material	Two Constituents	Synthesized/ Controlled	Properties Predictable	Engineering Composite
Fiberglass/Epoxy	Yes	Yes	Yes	Yes
Cast Iron	Yes	No	No	No
Steel/Polypropylene	Yes	Yes	Yes	Yes
D.S. Eutectic	Yes	partially	Yes	Yes
Adobe Brick	Yes	Yes	Yes	Yes
Wood	Yes	No	No	No
Bone	Yes	No	No	No

The ability to synthesized materials to predictable properties allows the designer to optimize the properties of the structure with respect to the magnitude and directions of the loads.

RATIONAL FOR COMPOSITE MATERIALS

Compared to conventional engineering materials, composites can be designed to produce exceptional strength and stiffness with minimum weight. A measure of these attributes are the so-called “specific properties” in which the either strength or stiffness are divided by density (Fig.1).

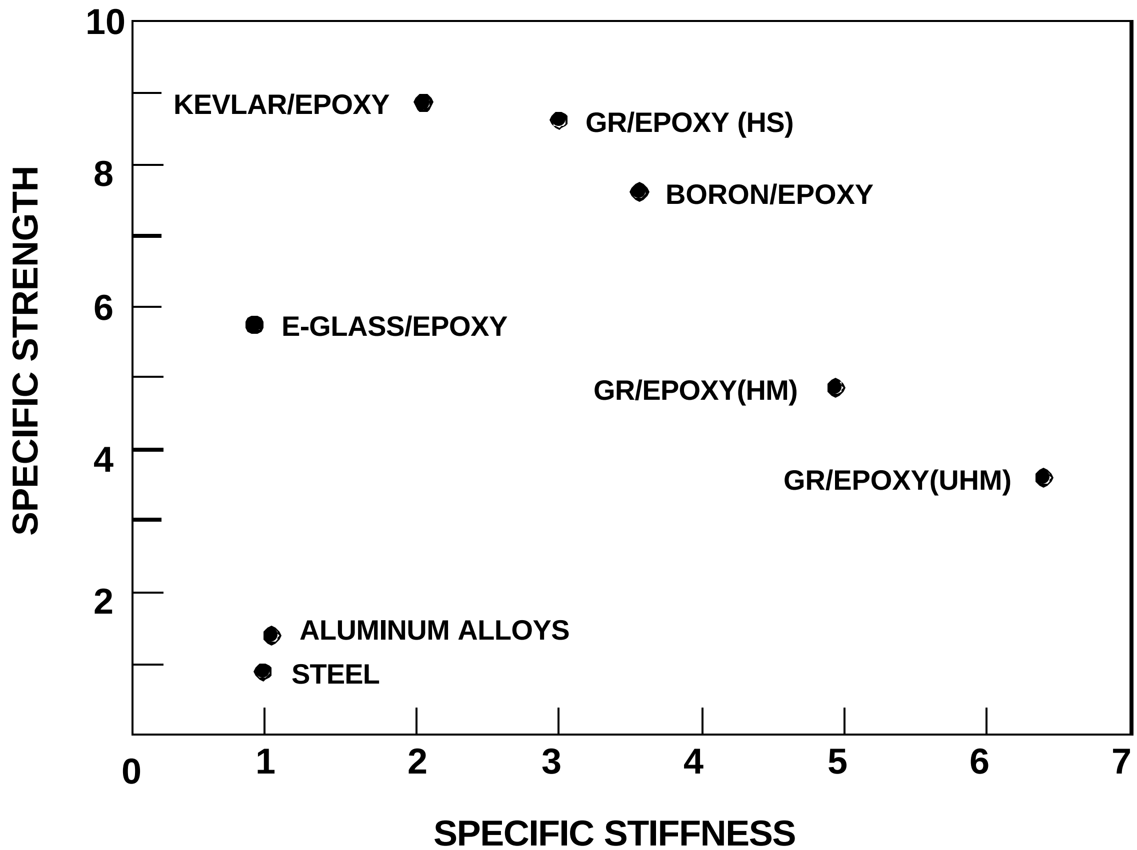


Figure 1-1. Relative Strength and Stiffness (Compared to Steel) of Various Composites and Aluminum Alloys

<u>REINFORCEMENTS</u>

The reinforcement is the dimensionally controlled constituent (fixed geometry) that can either be particles, fiber or flakes. In many cases the reinforcements have unique properties that contribute significantly to the properties of the composite. Particle reinforcements can be considered point bodies in which the size as measured by the radius is the critical dimension. The important dimension for the fiber reinforcement is its length or the length to diameter ratio. For flakes the area or area to thickness control the properties of the composite.

The most common form of reinforcement for polymer matrix composites are fibers. The fibers carry the majority of the load and contribute to most of the stiffness in polymer composites since the matrix stiffness is usually only a very small fraction (1/10 to 1/100) of the reinforcement stiffness. The fibers can be either continuous or discontinuous.

In metal matrix composites both fibers and particulate reinforcements are commonly employed. The matrix stiffness is typically ¼to 1/5 of the reinforcement stiffness. The matrix can then carry moderate fraction of the load. For ceramic matrix composites, particulates are most common.

Textile Fibers

Textile fibers or their derivatives are commonly used as reinforcements. They can be woven, braided or knitted into precursor forms prior to infiltration by a matrix. Generally the fibers are 25 μm or less in diameter, and in their original form are continuous. Fibers can be polymers, carbons or ceramics, examples of which are given in the following list:

- Polymers - rayon, polyacrilonitrile, Kevlar®, Nomex®, nylon
- Carbons - graphite, carbon, Celiox®
- Ceramics - glass, alumina, Nextel®, silica, silicon carbide

Textile Forms

The fiber precursor is drawn, extruded or spun as a group of individual fibers. These groups are referred to as *strands*, *ends* or *tows* depending on the industry. Glass fiber groups are called "strands" while carbon fiber groups are called "tows". A typical fiber count in a carbon tow is 3,000. Strands or tows can be collected into larger groups called *roving.* Roving can be woven into heavy coarse fabrics or chopped to produce staple that can be pressed into mat or felt. To produce a fine textile the strands or tows can be given a slight twist (less than one turn per inch). Twisted strands are called *yarns*. Twisting single strand yarns together can produce heavy yarns.

Textile Terminology

A variety of fabrics can be woven from these yarns. Yarns that lie in the lengthwise or machine direction are called *warp* yarns. The yarns that lie in the cross-wise direction are called *fill* yarns. There are five commonly used weave patterns used in composite construction.

Plain Weave – One warp yarn passes over and under one filling yarn. This pattern has maximum stability with respect to slippage and fabric distortion.

Basket Weave – Two or more warp yarns interlocking over two or more filling yarns. This pattern has greater pliability than plain weave.

Twill Weave – One or more warp yarns over and under two or more filling yarns. This produces a very drapeable fabric.

Crowfoot Satin Weave – One warp yarn interlocking over three and under one filling yarn. This pattern can conform to very complex contours.

Eight-harness Satin Weave – One warp yarn interlocking over seven and under one filling yarn. This pattern produces the highest strength composite.

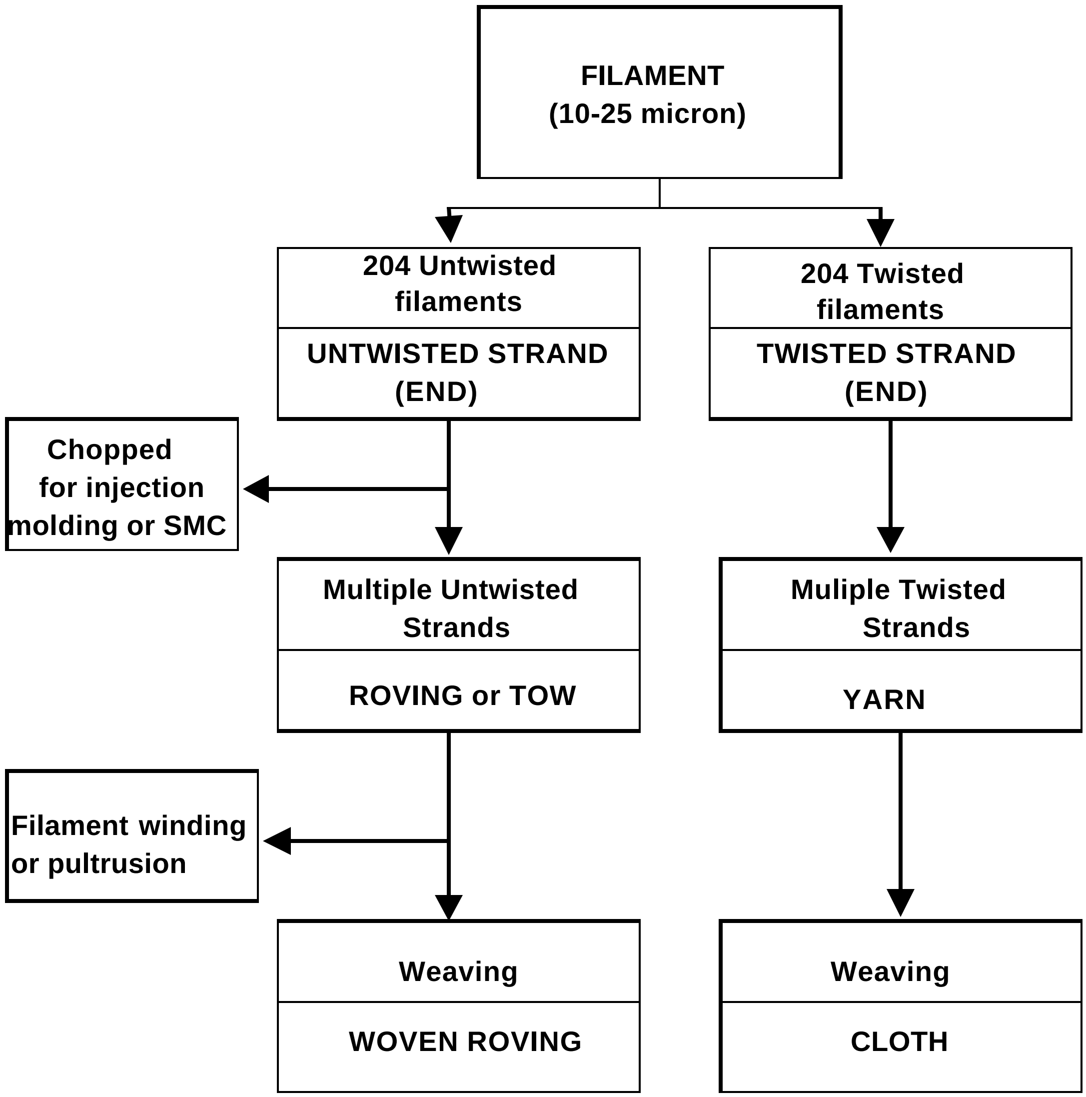


Figure 1-2 Use of filaments in composites.

Monofilaments (25 micron to 200 micron, continuous)

Monofilament fibers are produced as a single strand by chemical vapor deposition or single strand drawing. They are generally much more expensive than textile fibers. Some typical monofilaments are:

- Boron on W, boron on carbon
- SiC on W, SiC on C
- Sapphire
- W, Mo, steel, Be

Whiskers (< 1 micron, discontinuous)

Whiskers are very fine nearly perfect single crystals that have near theoretical strength and stiffness. They are generally produced by vapor deposition.

- Common metal whiskers include: Fe, Cu, Ni
- Silicon carbide, alumina and boron carbide are common ceramic whiskers. They are used for metal matrix and ceramic matrix composites. The largest application of whiskers in a commercial product is silicon carbide reinforcement of aluminum oxide for cutting tool inserts.
- Carbon whiskers have limited commercial use.

All whisker forms are expensive and generally avoided because of potential health hazards.

<u>MATRIX</u>

The matrix is the continuous phase of the composite that holds the reinforcement in place. The functions of the matrix include: holding the fibers in place, protecting the fibers from reaction with the environment, transmitting load from fiber to fiber and protecting the fibers from mechanical abrasion. Each type of matrix has unique properties, Table 1-2 that dictates their selection.

- *Polymers*: Thermosets, thermoplastics – These matrix materials contributes very little to strength and stiffness. They are used primarily to hold the reinforcements in place. Thermosets are particularly useful because they can be processed easily and relatively inexpensively.
- *Metals*: Al, Ti, superalloys – These matrices have a significant but usually not dominating contribution to strength and stiffness. They provide both high temperature strength and transverse properties. They are also selected when thermal and electrical conductivity are required. As the melting temperature of the matrix alloy increases the processing cost increases. Metal matrices tend to react with commonly used fibers, therefore requiring the fibers to have a protective coating to survive processing.
- *Ceramics*: Glass-ceramics, ceramics – These matrices provides the dominant contribution to strength and stiffness of the composite. The role of the fiber in ceramic matrices is to increase the ceramics toughness. Incorporating fibers into ceramic matrices is generally more difficult than for metal matrices because of their significantly higher melting temperature.

- Carbons: Pyrolytic graphite, amorphous carbon – These matrices are used primarily for high temperature strength and thermal ablasion applications such as rocket nozzles and reentry bodied.. The process for incorporating fibers into carbon laborious, slow and expensive. The largest commercial application for pyrolytic graphite is for aircraft brakes.

Table 1-2 Matrix materials for engineering composites

Matrix Type	Positive Attribute	Negative Attribute
Thermoset resins	Low cost processing	Brittle
Thermoplastic resins	Tough Formable	Low thermal and solvent resistant High cost to process for filament
Carbon	Very high temperature applications	Very high cost to process
Light metals	Thermal resistant Conductive Electrical and thermal	Reacts with most fibers
Superalloys	Oxidation resistant	Heavy
Refractory	High temperature strength	Heavy No oxidation Resistant
Glass	Corrosion resistant Thermal expansion	Brittle
Glass/ceramics	Corrosion and temperature resistant	Brittle and expensive
Ceramic	Very high temperature Oxidation	Expensive

<u>TERMS COMMONLY USED IN COMPOSITE SCIENCE AND TECHNOLOGY</u>

Anisotropic - Material properties are different in all directions.

Orthotropic - Material properties are different in three mutually perpendicular directions.

Isotropic - Material properties are the same in all directions. Almost all engineering alloys such as aluminum and steel in the annealed condition are isotropic.

Preferred Orientation - A material that has some degree of anisotropy is said to have preferred orientation. Highly wrought alloys including aluminum and steel will have different properties in the direction of elongation. Drawn wire and extrusions a well known examples.

Random Orientation - A material that is said to have random orientation possesses some degree of isotropy. Engineering alloys are made up of an assembly of crystals, each of which may be orthotropic but on a macroscale exhibits apparent isotropy.

Homogeneous -Properties are the same from point to point in the material. This effect is very scale dependent. Even a material that consists of two or more phases or constituents can be apparently homogenous if the sample of consideration is not too small. Most engineering alloys are considered homogeneous by this standard. Composites which have macro-sized constituents would require a larger sample size to appear homogeneous

Heterogeneous - Properties are different from point to point in a material. On a fine enough scale almost all alloys are heterogeneous.

Lamina - A single layer containing reinforcements in the plane of the layer. This is the usual building block for design and fabrication of composite structures.

Laminate - A laminate is a stack of lamina (usually with alternating or varying principal directions). The laminas are arranged in a particular way to achieve some desired effect.

Micromechanics - Predicts composite behavior from the interaction of constituents on the appropriate scale. In whisker composites the appropriate scale is a fraction of a micrometer. For reinforced concrete the appropriate scale is several centimeters.

Macromechanics - Predicts composite behavior by presuming homogeneous material. The effects of constituents are detected only as averaged apparent properties.

CLASSIFICATION SCHEMES

Composites are classified by various criteria for the convenience of the industry. Matrix type is often used to describe composites. The most common designations based on matrix type are PMC (polymer matrix composites), MMC (metal matrix composites) and CMC (cceramic matrix composites). Table 1-3 lists some of the mechanical characteristics of these three types of composites.

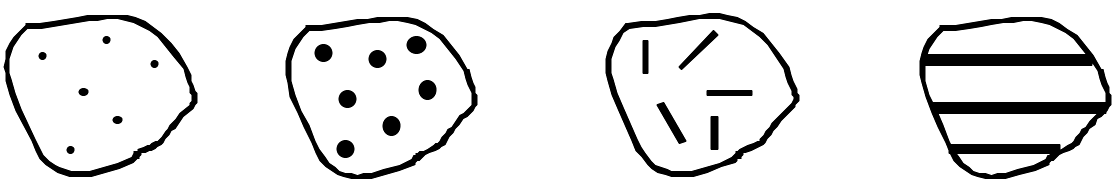
Composites are also classified by the shape or continuity of the reinforcement. They can be described as continuous or discontinuous relative to their continuity and as particulate or fiber relative to to the shape of the reinforcement. Illustrations of these types of composites and some of their characteristic properties are seen in Fig. 1-3. Figure 1-4 describes the effect of reinforcement shape and size on composite strengthening. Table 1-4 list some examples of composites using this classification.

Table 1-3 Composites classified by matrix type

Matrix Type	Common Designation	Matrix Properties			Most Effective Reinforcement
		Stiffness	Strength	Ductility	
Polymer	PMC	Low (0.2 TO 0.5) msi	Low (0.5 TO 5) ksi	Low (< 2%)	Continuous Fiber
Metal	MMC	Moderate (6 TO 16) msi	High (10 TO 150) ksi	High (20%)	Continuous and Discontinuous Fiber
Ceramic	CMC	High (20 TO 80) msi	High (20 to 80) ksi	Low (< 1%)	Discontinuous Fiber or Whisker and Particulate

PARTICULATE COMPOSITES **FIBER COMPOSITES**

DISPERISION STRENGHTENED **PARTICLE REINFORCED** **FIBER OR WHISKER REINFORCED** **CONTINUOUS FIBER**



3-0 **3-0** **3-0** **3-1,3-2**

conventional fracture mechanics

single crack

fracture mechanics

multiple cracks

modified fracture mechanics

multiple cracks

Figure 1-3 Composites classified by reinforcement shape, or continuity.

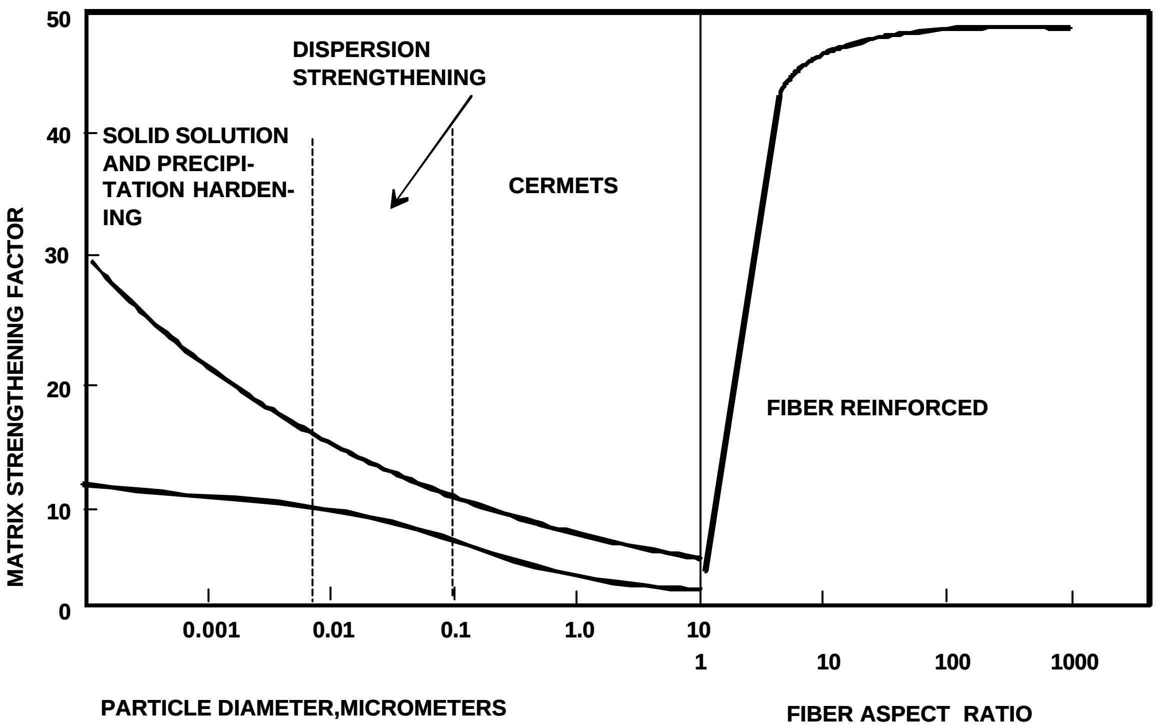


Figure 1-4 The effect of reinforcement size and shape on strength

Table 1-4 Composites classified by Shape and size of reinforcement

Type	Examples	Strengthening Mechanisms	Load Bearing Member	Manufacturing Process	Reinforcement Characteristic
Dispersed	Ni-NiCr ODS alloy SAP Age-hardening alloys	Inhibits dislocation motion - Generation - Motion	Matrix	Powder Internal oxidation Precipitation from solid solution	Small Particles 10^{-2} to 10^{-1} µm $< 0.2\ V_f$
Particulate	Cemented carbides SiC_w/Al Filled polymers Glass ceramics TT ceramics	- Matrix contraction - Particle strength - Residual stress - Control flaw size - Microcracking - Transform tough - Crack bridging - Crack deflection	Shared by phases	Powder methods Precipitated from solid solution Crystallized glass Directional oxidation Sol chemistry	Large particles >1µm typically (5-10µm) 0.1 to .95 V_f Spacing = 8
Fiber Composite	GRP CRP C/Al SiC/Ti SiC fiber /Glass DSE	- High F_f - High E_f - Toughness of interface - Residual stress	Fibers Fiber & Matrix in MMC	Resin impreg Melt infiltrat Diff. bonding Lanxide Solgel process Control solidification.	Fibers in matrix Alignment Aspect ratio