A100

Fundamentals of composite materials

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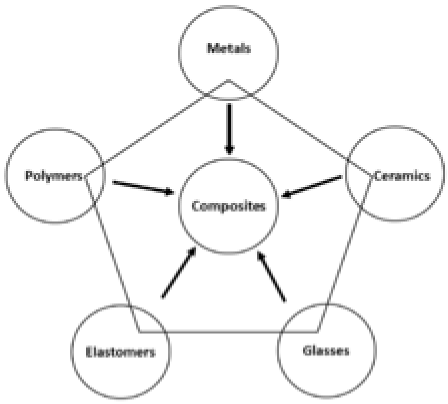
Overview[edit | edit source]

What is a composite material?

A composite material is a combination of two or more materials of distinctly different chemical or physical characteristics. Working together in collaboration, they create a new material combination of enhanced properties and characteristics that neither material on its own can provide.

As a newly created material capable of unique properties and characteristics, composites are generally accepted as an additional class of the engineering materials.



The material classes as defined by Ashby. Reproduced from [1]. Note: many sources group together Polymers with Elastomers (as Polymers) and Ceramics with Glasses (as Ceramics) [2].

Classes of Engineering Materials:

- Metals
- Polymers
- Ceramics
- **Composites**

While the combinations of materials are limitless, the Knowledge in Practice Centre (KPC) primarily focuses on material combinations of polymers reinforced with fibres of various materials. Often referred to as fibre reinforced polymers (FRPs), these include the commonly-known glass fibre and carbon fibre (composite) materials.

What are the advantages of composite materials? The material properties achieved by purposeful material combinations can give composites advantages that cannot be achieved by conventional single engineering materials. Advantages may be high stiffness or strength to weight ratio (think airplane or race car), tailorable stiffness or high elastic storage modulus in defined load directions (think kayak paddle or hockey stick).

Where are composite materials used? Composite materials are used in a wide range of applications from aerospace structures, to boat hulls, to sporting goods. For example, composite materials enable us to fly further and develop more fuel-efficient automobiles (vehicle weight reduction), harvest energy more efficiently (lighter and larger wind turbine blades), prevent injury (safety equipment like motorcycle helmets), and enjoy recreational activities (sporting equipment).

Composites market:

- Aerospace
- Automotive
- Sporting goods
- Marine
- Consumer goods
- Construction/civil structures
- Industrial applications

Learn more, view KPC AIM Event webinar:

- Click here to view the KPC AIM Event: Composite materials engineering webinar session 1 - Introduction

History of Composites[edit | edit source]

Origins of composite materials[edit | edit source]

The use of composite materials dates back to ancient Egypt, Turkey, and Mesopotamia, where civilizations combined natural materials such as straw to reinforce mud and clay in bricks and pottery. The concept of a laminated structure making use of fibre orientations is also suggested to have originated in ancient Egypt in 3400 BCE in the form of plywood. In the 1200s, the Mongols were credited as having developed the first composite bow, using a sandwich structure made of animal bone, ligaments, wood, pine resin, and other natural materials[3].

1900s[edit | edit source]

Modern day, advanced composites are relatively new with their history originating in the early 1900s with the development of artificial plastics and thermosetting resins such as Bakelite in the USA. In 1913, the concept of pre-impregnation was filed in a patent and in 1916 another patent was filed for a composite airplane propeller. It wasn't until the 1930s, however, with the first industrial processes for making glass fibres, that fibre reinforced polymers (FRPs) were born. World War II promoted the production of FRPs, which led to the introduction of glass fibre reinforced polymers (GFRPs) being used in airplanes, automobiles, boat hulls, and even surfboards. In the late 1950s and early 1960s carbon and aramid fibres were introduced to the world, with breakthroughs in research occuring in the USA, UK, and Japan[3][4]. This has since revolutionized the composites industry. Owing to their attractive strength-to-weight properties, the aerospace industry began adopting carbon fibre reinforced polymers (CFRPs) and has since led in the advancement of composite material design and manufacturing.

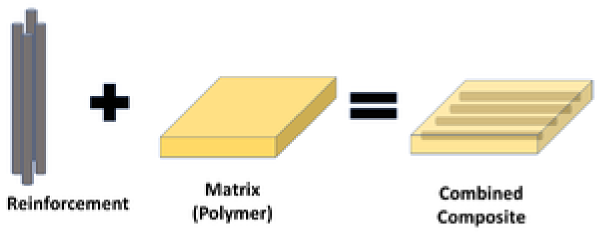
Modern day[edit | edit source]

In 2009, Boeing unveiled the 787 Dreamliner, a commercial airliner comprising of 80% composites by volume. Today, composite materials have found use in a wide range of markets from specialized applications to consumer products.

Composites market:

- Aerospace (airplanes, space launch vehicles)
- Automotive (automobile bodies, panels, beams)
- Sporting goods (skis and snowboards, helmets, hockey sticks, bicycles, fishing poles)
- Marine (boat hulls)
- Consumer goods (computer and cellular phones)
- Construction/civil structures (bridges)
- Industrial applications (electrical insulators, piping)

Main Constituents of a Composite Material[edit | edit source]



The material parts (constituents) that form a fibre reinforced polymer (FRP) composite material.

Composite materials are formed by combining two material parts or components, referred to as constituents:

- **Reinforcement** material (the load bearing material) - generally stiffer and stronger
- **Matrix** material (the binding / hold everything together material) - generally less stiff and weaker

The two materials comprised together in the form of a composite material, where the matrix is the continuous material phase, while reinforcement is the dispersed material phase. The matrix material component is used to classify the type or family of the composite material.

Broadly speaking, there are three main families of composite materials:

1. Polymer matrix composites (PMC) – the focus in the KPC
2. Metal matrix composites (MMC)
3. Ceramic matrix composites (CMC)

The typical industry naming convention for composite materials makes reference to both the reinforcement and the matrix material constituents. For example, fibre reinforced polymer (FRP) refers to fibre reinforcement form, and polymer matrix. More detailed naming examples include glass fibre reinforced polymer (GFRP) – often just referred to as glass fibre (or fibre glass) composite, and carbon fibre reinforced polymer (CFRP) – referred to as carbon fibre composite; indicating the reinforcement material and form, and matrix material class respectively.

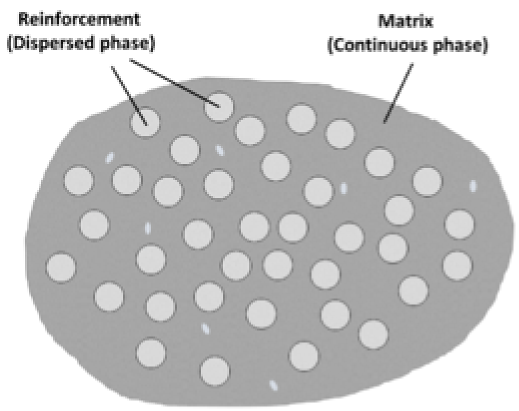


Illustration of the composite material constituent phases. (Matrix - continuous phase, Reinforcement - dispersed phase)

How the reinforcement and matrix material components are combined together to form the composite material is the subject matter of composites processing. See here for some common industry composite manufacturing process examples.

For further material information than of what is provided on this page, see the Material Structure page in the Foundational Knowledge volume.

Reinforcement material[edit | edit source]

Link to Reinforcement Structure on the Material Structure page in Foundational Knowledge

The reinforcement component is responsible for the main load bearing capability in the composite material. Reinforcements can range from short discrete particles to long continuous fibres and woven fibre fabrics. Because of their load bearing function, reinforcement material are generally ceramic class materials, or high strength synthetic polymers.

In fibre reinforced polymers (FRPs), popular fibre materials include:

Ceramic materials	Polymer materials
Glass fibre	Aramid fibre (e.g. Kevlar)
Carbon fibre	Ultra-high-molecular-weight polyethylene fibre (e.g. Spectra)

For more information on reinforcement material choice, see the catalogue volume reinforcement material page.


Example of a composite laminate formed by stacking numerous layers (plies) of carbon fibre/epoxy prepreg material.

Matrix material[edit | edit source]

Link to Matrix Structure on the Material Structure page in Foundational Knowledge

The function of the matrix component is to bind together the reinforcement, to aid in the load transfer between the reinforcement, and to hold the combined composite material in the desired part shape. Other functions of the matrix include protecting the reinforcement from the environment, and depending on the reinforcement form – supporting the reinforcement in compression (e.g. fibre reinforcement).

Desirable characteristics of the matrix material:

- low density (for lightweight composite material)
- environmental resistance: chemical, moisture resistant
- processible: able to flow and surround the reinforcement material during the manufacturing process

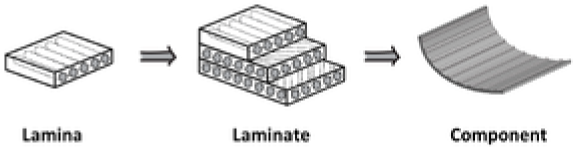
In fibre reinforced polymers (FRPs), the polymer makes up the matrix constituent. Both thermoset and thermoplastic polymers can be used as matrices.

Examples of popular polymer matrix materials:

Thermoset materials	Thermoplastic materials
Epoxy	Polyproplyene (PP)
Vinyl ester	Polyether imide (PEI)
Polyester	Polyether ether ketone (PEEK)

For more information on popular matrix materials, see the catalogue volume matrix page.

Laminate construction[edit | edit source]



Composite materials are typically constructed by laminating, or stacking layers of material (lamina) on top of each other that build up to the desired material structure.

When constructing FRP composite materials using long continuous fibre reinforcements, typically sheets of the reinforcement fibre material are stacked to form a laminate structure - giving rise to the commonly used terms of composite laminate, and lay-up. Using this laminate construction technique, the fibre orientations can be varied at each layer for a more efficient handling of the mechanical load through the material. See for the Material Structure page (Foundational Knowledge volume) for further explanation.

Composite Design and Manufacturing[edit | edit source]

Link to main Composite Design and Manufacturing page

Composites manufacturing practice is driven by the need to achieve a desired manufacturing quality, which in turn is governed by the manufacturing science. On one side, there exists the knowledge (science) base which defines 'why' the quality is as it is. On the other side, there is the practice of 'how' best to implement manufacturing processes to affect the quality in a given way. The interconnectivity and understanding of these two elements are important and form the basis of knowledge-in-practice thinking[5].

On the composite design and manufacturing page, you will find a general overview about the composite design and manufacturing practice.

Composite Processing and Manufacturing[edit | edit source]

Link to main Composites Manufacturing page

A composite manufacturing process is a collection of process steps transforming the raw material reinforcement and resin matrix constituents into a combined composite material of a desired part shape and geometry. The processing impacts both the final material properties and resulting part component performance. It also crucially determines the associated component production rate and production costs.

For examples of common composite manufacturing processes, see here (Composites Manufacturing - Common Process Examples).

In the KPC, we present a systematic approach to defining the manufacturing process. Specifically, we promote the idea that a process is nothing more than a set of equipment and tooling used to perform a specific action (or process step) on the part or material. Therefore, the manufacturing workflow is dictated by the steps performed by equipment and tooling.

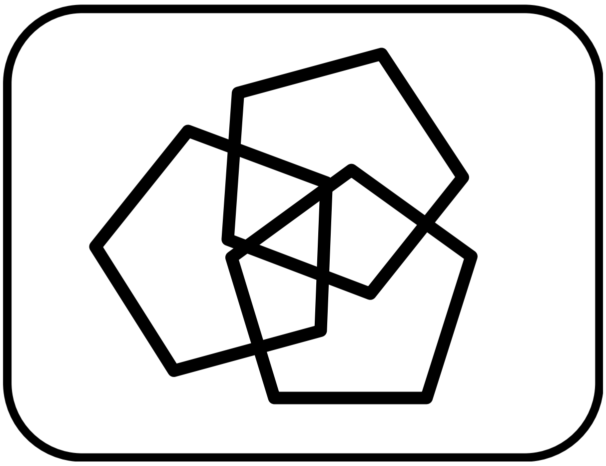
Learn about the CKN Knowledge in Practice Centre approach to systems approach to composites here.

Explore this area further

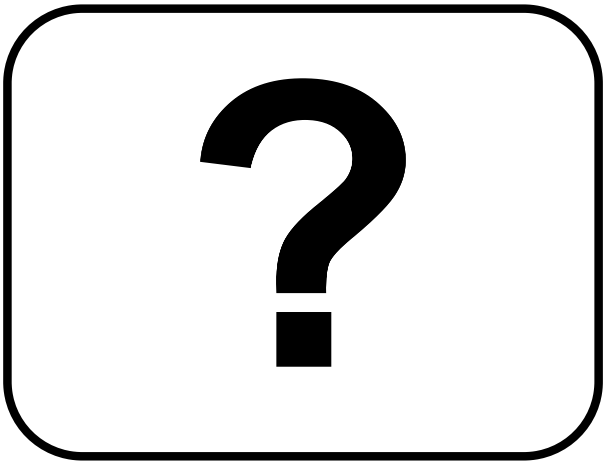
- Fundamentals of composite materials - A100
  - How Composites Differ From Metals - A342
  - When to Use Composites - A360
  - Composites design - A229
  - Composites manufacturing - A215

References

1. ↑ [Ref] Ashby, M.F. (2011). *Materials Selection in Mechanical Design*. Elsevier. doi:10.1016/C2009-0-25539-5. ISBN 9781856176637.
2. ↑ [Ref] Callister, William D. (2003). *Materials Science and Engineering: An Introduction*. John Wiley & Sons, Inc. ISBN 0-471-13576-3.
3. ↑ [3.0] [3.1] [Ref] Verpoest, Ignaas (2020). *50 Years of Composites: Past Present & Future*.
4. ↑ [Ref] Nagavally, Rahul Reddy (2016). "Composite Materials - History, Types, Fabrication Techniques, Advantages, and Applications". **5** (9). ISBN 9789386083692.
5. ↑ [Ref] Fabris, Janna Noemi (2018). *A Framework for Formalizing Science Based Composites Manufacturing Practice* (Thesis). The University of British Columbia, Vancouver. doi:10.14288/1.0372787.



About



Help

Engineered materials (designed to have specific properties) made from two or more constituent materials with different physical or chemical properties. The constituents remain separate and distinct on a macroscopic level within the finished structure.

Carbon fibres are composed of large aromatic sheets similar to those in graphite. These graphitic layers form the basic structural units in the shape of ribbons. The structure of carbon fibre ribbon is believed to be a columnar arrangement of disoriented graphite crystallites parallel to the ribbon length. The idealized tetragonal crystallites are stacked above one another, with slight disorientation between the crystals in the direction of fibre axis, trapping sharp needle like voids, where the boundaries between the stacks represent the disordered regions.

For polymer matrix composites (PMCs), resin refers to the matrix; the continuous material phase that binds the reinforcement together, maintains shape, and transfers load. Resins are divided into two main groups: thermosets and thermoplastics.

An acronym for Fiber-reinforced polymer, which is another term used for a composite material composed of fibre and polymer. This is sometimes expanded to GFRP or CFRP for glass fibre reinforced polymer or carbon fibre reinforced polymer, respectively.

The continuous material phase that binds the reinforcement together, maintains shape, transfers load, protects the reinforcement from environment and damage, and provides the composite support in compression.

Desirable characteristics:

- Moisture/chemical resistance
- Low density
- Processability

Polymer Matrix Composites (PMC).

Metal Matrix Composites (MMC).

Ceramic Matrix Composites (CMC).

Pre-impregnated (prepreg) material refers to fibre that is already combined with resin. It is the most common material form used in aerospace.

During prepreg production, (e.g. fibres are run through a resin bath), prepreg is heated and partially cured to B Stage (< 5 % degree of cure). Thermoset prepregs (e.g. epoxy prepreg) have to be kept in a freezer at around -20 °C. At room temperature, the epoxy starts to cure.

Thermosets are a class of polymer that undergo polymerization and crosslinking during curing with the aid of a hardening agent and heating or promoter. Initially they behave like a viscous fluid. During curing, they change from viscous fluid to rubbery gel (viscoelastic material) and finally glassy solid.

If heated after curing, initially they become soft and rubbery at high temperatures. If further heated, they do not melt but decompose (burn)

Comes in two parts: part A (resin) and B (hardener). When mixed, curing reaction starts and is not reversible.

Examples include epoxy or polyester.

A class of polymer, some common examples include polypropylene and polyethylene.

They soften and melt upon heating (i.e. potentially recyclable), high viscosity when melted, therefore difficult to saturate fibres. Usually needs a lot of pressure and heat to process.

Any manufacturing and/or decision making activity that occurs during any stage of the development design cycle (e.g. conceptual design to production).

In the context of Knowledge in Practice, practice refers to the systematic use of science based knowledge to reduce composites manufacturing risk, cost, and development time.

In the context of knowledge in practice, knowledge refers to the systematic use of science based knowledge in composites manufacturing practice.

There is a distinction between experience based knowledge and science based knowledge:

- Experience based knowledge (‘know-how’) is an understanding of potential outcomes and their relationships that is founded on pragmatism and experience accumulated over time in individual programs, companies and in the industry more broadly.
- Science based knowledge (‘know-why’) is an understanding of potential outcomes and their relationships, based on the important processing physics, that is mature enough to be codified using the appropriate governing laws and constitutive equations.