



Silesian University of Technology
Faculty of Civil Engineering

Almudena Casado Chacon
Superior Engineering Technical School
University Carlos III of Madrid

Composites Materials

Promotor: Prof. dr hab. inż. Marcin Górski

M. Sc. Eng. Thesis

Gliwice 2012

Table of content

Index of figures.....	4
1. Introduction.....	5
1.1 Definition and characteristics.....	5
1.2 Classification.....	6
1.3 Advantages and limitations	8
2. Organic Matrix Composites.....	10
2.1 Matrix.....	10
2.2 Reinforcement.....	12
2.3 Interface.....	13
3. Metal Matrix Composites	19
3.1 Introduction.....	19
3.2 Types of Matrix.....	19
3.3 Types of reinforcement.....	20
4. Ceramics Matrix Composites.....	22
4.1 Introduction.....	22
4.2 Types of fibers.....	23
4.3 Process for obtaining a composite material: sintered.....	24
5. Nanocomposites.....	26
5.1 Introduction.....	26
5.2 Nanoparticles.....	26
5.3 Nanocomposites structure.....	27
5.4 Techniques for preparing nanocomposites.....	28
5.5 Properties of the nanocomposites.....	30
6. Mechanical behavior of materials.....	31
6.1 Introduction anisotropic elastic behavior.....	31
6.2 Sheet micromechanics.....	37
6.3 Mechanical behavior of a rolling	40
6.4 Structural analysis of composite.....	45
7. Effects of environment on mechanical behavior.....	48
7.1 Hygrothermal effects.....	48
7.2 Solar radiation.....	50
7.3 Biological Effects.....	50
7.4 The ray.....	50
7.5 Space environment.....	50
7.6 Fire behavior.....	51
7.7 Chemical corrosion.....	53
8. Summary.....	55
9. Bibliography.....	55

Index of figures

Figure 1. Mechanical properties of the matrix, the reinforcement, and the composite material obtained from the combination of both. (Google images)	5
Figure 2. Diagram of the components forming the composites (Google images)	5
Figure 3. Types of fibers. (Google images)	6
Figure 4 . Types of composite structural material (Google images)	7
Figure 5. Contact angle (Google images)	13
Figure 6. Mechanical joint (Google images).....	14
Figure 7. Electrostatic Joint (Google images)	15
Figure 8. Chemical Joint (Google images)	15
Figure 9. Joint in interdiffusion (Google images)	15
Figure 10. Types of core (Google images)	18
Figure 11. Nano- particles (Google images)	27
Figure 12. Microcomposite (Google images)	27
Figure 13. Intercalated nanocomposite (Google images).....	28
Figure 14. Exfoliated nanocomposite (Google images)	28
Figure 15. Polymerization in-situ (Google images)	29
Figure 16. Polymerization in solution (Google images)	29
Figure 17. Polymerization collation melt (Google images)	29
Figure 18. Elastic problem (Google images).....	31
Figure 19. Orthotropic material (Google images)	35
Figure 20. Sheets	36
Figure 21. Failure modes	40
Figure 22. Statistical distribution of the tensile strenghs	41
Figure 23. Failure theory	45
Figure 24. Typical equilibrium curve of a thermoplastic polymer (Google images)	48
Figure 25. Glass transition temperature versus moisture content (Google images).....	49
Figure 26. Thermal effects on the carbon / epoxy function of temperature (Google images).....	51
Figure 27. Thermal degradation of a material glass / phenolic resin (Google images)	51
Figure 28. Inter-laminar shear strength depending on the temperature and time.....	52
Figure 29. Hardness in function of temperature and time	52
Figure 30. Flat shear strength depending on the temperature and time	52

1. Introduction

1.1 Definition and characteristics

A composite material is made from two or more constituent materials and the main characteristic is the properties of the final material are superior to those materials which have separate constituents.

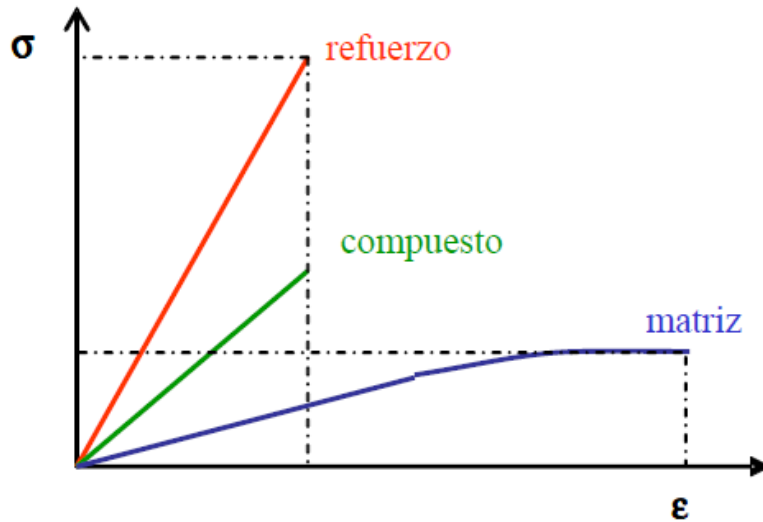


Figure 1. Mechanical properties of the matrix, the reinforcement, and the composite material obtained from the combination of both. (Google images)

The composites are formed by two phases: a continuous, matrix and a dispersed, reinforcement. The reinforcement provides the mechanical properties to the composite material and the matrix thermal and environmental resistance. Matrix and reinforcement are separated by the interface.

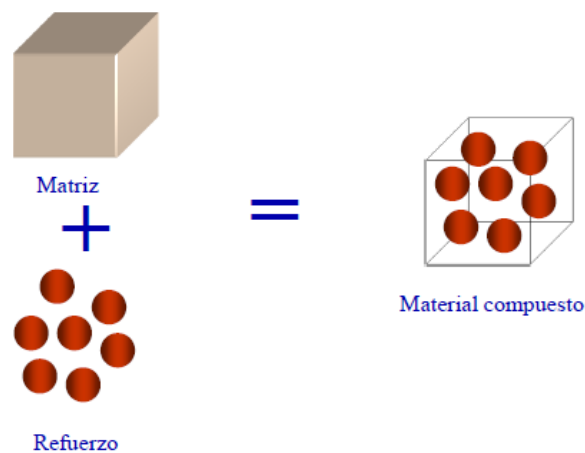


Figure 2. Diagram of the components forming the composites (Google images)

There can be no chemical reaction between components.

- Matrix

The main function that has the matrix is support the applied load and transmits it to the reinforcement through the interface and protects the fibers from the external environment and keep them together. . For this, the matrix must be deformable and must also have a good compatibility between matrix and reinforcement.

- Reinforcement

The reinforcement feature is to transmit loads to the matrix, thus defines the bulk of the material mechanical characteristics such as strength and stiffness. It can be a 20-80% by volume of the composite.

The properties of the composites depends on a several factors:

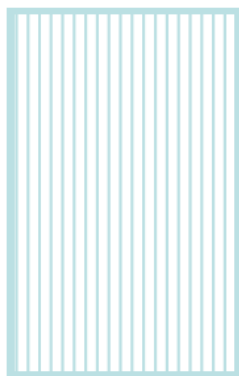
- a) properties of the matrix and reinforcement
- b) reinforcement content
- c) orientation of the reinforcement
- d) a method of production of the composite

1.2 Classification of composites

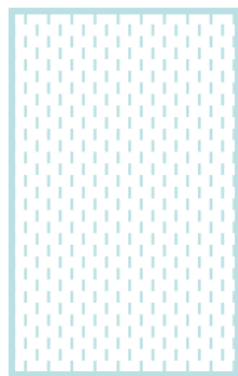
Composites can be classified according to the shape or nature of the constituents and by the size of the dispersed phase.

a. Classification according to the shape of the constituents

- Fibrous composites: The reinforcement is a fiber, a material with a length to diameter ratio too high. The fibers may be continuous or discontinuous (the latter may be random or unidirectional).



Continuous



Discontinuous and aligned

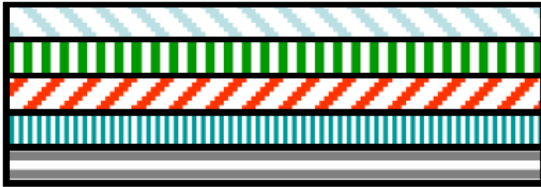


Discontinuous and randomly oriented

Figure 3. Types of fibers. (Google images)

- Particulate composites: The reinforcement is formed by particles which dimensions are approximately equal in all directions.
- Composite structural materials are formed by the composite materials and homogeneous materials. Laminates or sandwich panel are the most used.

Laminates composites



Sandwich Panel

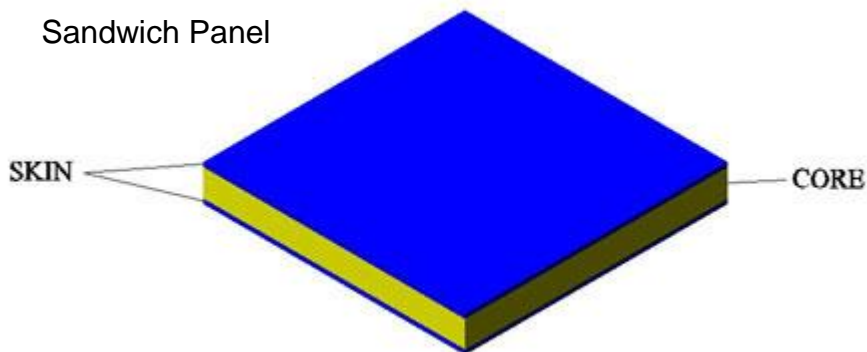


Figure 4 . Types of composite structural material (Google images)

b. Classification according to the nature of the constituents

- Organic matrix composites

The main characteristics are:

- Have low density
- Be able to obtain complicated components
- Be the most currently used

Its disadvantages include the lack of resistance to fire.

- Metal Matrix Composites

The main characteristics are:

- Increased service life
- High thermal and electrical conductivity
- Stability against moisture
- Higher wear resistance

Its main disadvantage is its high price

- Ceramic Matrix Composites:

Its advantage is its high strength at elevated temperatures and its main disadvantage their brittleness and low resistance to thermal shocks.

c. Classification according to the size of the dispersed phase:

- Microcomposites or conventional composites

The size of the reinforcement is on the order of a micron (10^{-6} meters). Mechanical properties are improved, but present processing problems. It is impossible, get films or fibers.

These problems result from the difference in size between the reinforcement and the matrix components. This difference gives rise to weak interactions.

- Nanocomposites

The size of the reinforcement is the order of nanometer (10^{-9} meters). In this case, the matrix reinforcement interactions occur at the molecular level.

1.3 Advantages and limitations

Several applications require materials with low current density and good mechanical properties. With conventional materials sometimes can't be achieved. The development of composites has allowed the improvement of the properties of materials, such as: high resistance, underweight, flexibility, dimensional stability, high dielectric strength, capacity building parts, corrosion resistance variety of finishes

Limitations:

- It is a new technology, which still is under investigation
- The calculation tools are not as well known or widely extend to metals
- Lack of information on behavior
- Need for strict control of manufacturing and material properties that depend on the method used
- High prices of matrices and fibers
- Reduction in ductility of the materials

2. Organic Matrix Composites

2.1 Matrix

Polymeric matrices can be thermoset or thermoplastic on the basis of whether or not to crosslinks.

a) Thermoset

Thermoset matrix has covalent linkages formed in the reaction reticulation. Their characteristics are: easy processing before curing (due to low molecular weight resin precursor), high tenacity, and more fragile than the thermoplastic.

Obtaining thermoset matrix occurs in two stages: partially polymerizes the monomer forming linear chains (polycondensation) and complete curing under heat and pressure (crosslinking). These matrixes are rigid, insoluble and not meltable.

The following table compares the most important thermosetting resin

Resin	Advantages	Disadvantages
Unsaturated polyester	<ul style="list-style-type: none"> ○ They are easy to process and which can be crosslinked even at room temperature ○ They have good chemical resistance ○ They have low prices 	<ul style="list-style-type: none"> ○ The shrinkage on cure is high ○ The curing reaction is highly exothermic and this can cause damage to the material ○ The high emissions occur crosslinking styrene ○ The mechanical properties are averages
Vinylester	<ul style="list-style-type: none"> ○ Good chemical resistance and corrosion ○ Good adhesion 	<ul style="list-style-type: none"> ○ They more expensive than polyester resins
Phenolic	<ul style="list-style-type: none"> ○ Give rise to flame retardance and low smoke emission and toxic gases. 	<ul style="list-style-type: none"> ○ Water is formed during curing to be removed to avoid defects in parts ○ The mechanical properties are low
Epoxi	<ul style="list-style-type: none"> ○ The mechanical properties are excellent ○ The degree of shrinkage during curing is low ○ Its thermal resistance is high 	<ul style="list-style-type: none"> ○ Its high price ○ The curing of the resin is slow

Table 1. Comparison of resin

b) Thermoplastic matrix

Thermoplastic matrix are not permanent joints; they are composed of linear molecules linked by single bonds above a certain temperature begin to flow and cool below that temperature back to its solid state.

Processing the thermoplastic comprises a heating step to soften the material and make the casting and a subsequent cooling phase to toughen it. Heating is usually done after the material to perform the molding.

The general advantages are: good chemical resistance, low moisture absorption, good mechanical properties, high production rate due to shorter molding cycle, parts can be easily repaired to soften the components by heat and join the parts, they are recycle, accepted unlimited storage compared to thermoset to be stored under controlled temperature and moisture.

Among the drawbacks of thermoplastic matrices are:

- Tendency to creep at elevated temperatures
- To have good mechanical properties molecular weight should be high and therefore the viscosity as well. This results in that the impregnation of the fibers is difficult.
- Require elevated temperatures and pressures for molding

The following table compares the most important thermoplastic resin

Matrix	Features
Polypropylene	<ul style="list-style-type: none"> ○ It is the most commonly used as matrix thermoplastic. ○ The addition of PP reinforced presents recyclability: good mechanical properties and thermal ○ The density is the lowest among the thermoplastic
Polyethylene terephthalate	<ul style="list-style-type: none"> ○ Greater transparency ○ Creep resistance ○ Good resistance to fire ○ Good electrical
Polycarbonate	<ul style="list-style-type: none"> ○ Highly transparent (amorphous) ○ Good dimensional stability ○ Good resistance to fire
High performance thermoplastic	They have a highly aromatic structure provides a high mechanical and thermal resistance.

Table 2. Comparison of matrix

2.2 Reinforcement

The reinforcement feature is to transmit loads to the matrix, the most used are the fibers below explains the most used.

A. Fiberglass

It is the most often used because: their specific mechanical resistance is superior to that of steel, good properties /cost, dimensional stability, ease of fabrication and good heat resistance.

➤ Type of Fiberglass

There are several types that differ in their chemical composition and therefore

Types	Features
E (electric)	The most widely used for its good properties / price.
R (resistance) and S (strength)	Good mechanical properties.
C (chemical)	Its good chemical resistance
D (dielectric)	Excellent dielectric properties

Table 3. Types of fiberglass

➤ Characterized

Characterized by two values:

- Title: Relation between weight and length of a thread (depends on the diameter and number of strands in a wire) (g / km).
- Weight: weight ratio of a tissue and its surface (g/mm²)

B. Carbon fiber

The advantages of the carbon fiber are: chemical resistance, low coefficient of thermal expansion, high specific properties.

On the other hand are expensive and high in contact with metals potential difference is generated which causes corrosion

➤ Types:

Fibers HT (High Toughness): worse mechanical properties properties (although they are better than those of glass fiber) and lower price.

Fibers HM (High Modulus): best mechanical properties and higher price.

C. Polymer fibers

a) The most used are aramid fibers (trade name Kevlar).

Have an elastic modulus higher than the glass fiber but lower than the carbon. They are used when you need good mechanical properties and lightness.

b) The properties of polyethylene fibers are similar to those of aramid fibers but its low melting point makes their properties rapidly decrease with temperature. It also has poor adhesion to the matrix.

D. Reinforcement hybrid materials

They are formed by the combination of two or more types of fibers. The most used combination comprises glass fibers and carbon in the polymer matrix. The compound obtained has better properties than if it had only fiberglass and is cheaper than if it were composed only of carbon fibers.

The fibers can be aligned and intimately mixed or can be laminated in alternating layers.

2.3 Interface

The mechanical properties of a composite material also depend on the hue and fiber bonding between the interfaces. It is especially important:

- The bond between fiber and matrix
- The transmission of mechanical stress between the two

This depends mainly on the treatability, because the composite material for the matrix should be in fluid state and wet out the reinforcement.

Treatability or wetting is defined as the ability of a liquid to spread over a solid surface. A good impregnability means that the matrix flow perfectly on the surface of the reinforcement and displace all air.

We can determine the treatability, mathematically, using the contact angle.

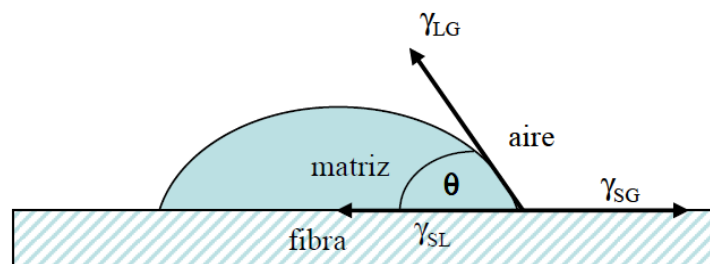


Figure 5. Contact angle (Google images)

Where:

γ_{SL} → solid-liquid surface energy(fiber-matrix),

γ_{SG} → surface energy (fiber-matrix),

γ_{LG} → liquid-gas surface energy (matrix-air)

$$\cos \theta = \frac{(\gamma_{SG} - \gamma_{SL})}{\gamma_{LG}}$$

Equation 1.

If $\cos \theta = 180^\circ \rightarrow$ the drop is spherical with a single point of contact between the liquid and solid. In this case there is no impregnation.

If $\cos \theta = 0^\circ \rightarrow$ As the contact angle is 0° there is a perfect impregnation.

In general, it is considered that the liquid does not permeate the solid if the contact angle is greater than 90° .

1) Joint at the interface

There are different types of bonding at the interface:

- Mechanical joint: The roughness between the two surfaces resulting in the union. A rougher more effective the union at the interface. This type of union is ineffective for tensile shear but effective.

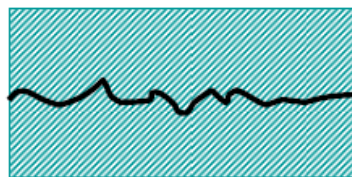


Figure 6. Mechanical joint (Google images)

- Electrostatic joint: This type of bonding occurs when one surface is positively charged and the other negative.

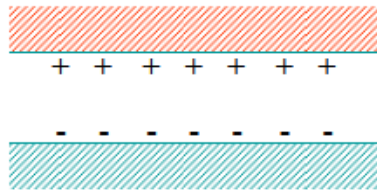


Figure 7. Electrostatic Joint (Google images)

- Chemical joint: It occurs when the fiber surfaces have chemical groups compatible with chemical groups of the matrix. The bond strength depends on the number of joints per unit area.

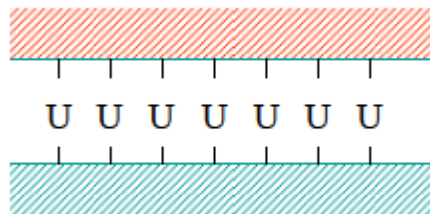


Figure 8. Chemical Joint (Google images)

- Joint in interdiffusion: In this type of joint surface of the reinforcement and the matrix polymer chains that have spread among them. The resistance of this binding is dependent on the number of interlacing between chains and increases with the addition of solvents or plasticizers.

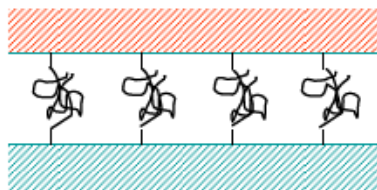


Figure 9. Joint in interdiffusion (Google images)

2) Architecture of the organic matrix composite materials

Given the architecture of the organic matrix composites, two types of composites:

a) Reinforced Plastics: matrices consist in introducing fiber reinforced or particle type.

The properties of the composites depend basically on the volumetric ratio of fiber / matrix and management of the fibers in the matrix:

- Effect of fiber volume fraction

By increasing the volume fraction of fibers in the composite material is obtained higher modulus of elasticity and resilience.

Technologically, composite materials with disperse phases in the form of fibers are the most important since they allow achieving high strength and rigidity at low density.

- Management of the fibers in the matrix

The relative orientation also influences the properties of the composite material can be aligned parallel | random alignment. The continuous fibers are aligned, whereas the staple fibers can be present aligned or randomly oriented.

- Composites with continuous fibers and aligned: the properties are dependent on the direction in which are measured (anisotropy). The longitudinal direction is the one with higher degree of reinforcement. In the direction transverse reinforcement is practically zero. Efforts in other directions are applied resistance between these extremes.

Most layered compounds consist of several layers with fibers aligned in different directions. Thus, the material can be efforts under multidirectional.

- Composite materials and aligned discontinuous fiber: the effectiveness of reinforcement is less, but the cost is lower and it is possible to obtain parts with complicated shapes.

- Composites with discontinuous fibers randomly oriented: are used when the fibers are completely subjected to multidirectional efforts since they are isotropic materials.

b) Structural composites:

They are composed of homogeneous and composite materials and their properties depend not only on the constituent materials but of the design geometry of the structural elements. There are two types: laminar composites and sandwich panels.

- Laminates

These composites are composed of stacked sheets and joined by means of an adhesive.

The focus of each sheet can be:

- One-way: when all fibers are parallel.
- Bidirectional: when half of the fibers are oriented at right angles with respect to the other half.
- Multidirectional: in this case the material is isotropic.

Gives each sheet properties depend on the following factors:

- Fiber Nature
- Presentation of the fiber (roving, mat, fabric, etc ...)
- Percentage of fiber
- Orientation: the material is characterized by a stacking sequence, or definition of the orientation of each sheet on an arbitrary reference axis.

When defining the stacking sequence must take into account a number of factors:

- The strength and stiffness in one direction depends on the orientation of the fiber.
- The most commonly used conventional orientations are 0, 90, + / -45. The right combination of these guidelines to control the strength and stiffness in any direction. It is possible use different orientations, but in general only complicate the fabrication of the structure.
- The laminate should always be symmetrical about its mid plane, and balanced to avoid anomalous distortions of the structure due to temperature changes.

- Sandwich materials

A sandwich structure is mainly composed of three elements:

a) Wings: composed of a thin, strong and usually with better properties than the other components. It is characterized by its rigidity and its resistance to compression.

b) Core: is a light whose main function is to separate the wings and transmit the shear forces from one wing to another. It is characterized by its low stiffness and tensile strength.



Figure 10. Types of core (Google images)

c) The binding interface between the wings and the core, which is intended to keep together the core and the wings and allow the transfer of costs between the two.

The sandwich materials have the following advantages:

- High specific strength and stiffness
- Thermal and acoustic insulation
- Large energy absorption capacity

Among its disadvantages highlights the complexity of quality control.

Elements	Materials	Features
Wings	Metal: steel and aluminum alloys	-High tensile, compression impact and abrasion -High rigidity -Good surface finish -Resistance to environmental factors
	Nonmetallic: plywood, cement, polymer matrix composites reinforced with fiber.	
Core	Corrugated core	-Low density -Shear strength -Stiffness perpendicular to the faces -Thermal insulation
	Honeycomb core	
	Balsa core	

Table 4. Types of materials to wings and core

3. Metal Matrices Composites

3.1 Introduction

Metallic matrix replaced in some applications the polymer because of the following properties:

- High strength and modulus
- High resistance to temperature
- Thermal and electrical conductivity

The metal matrix composite materials are used primarily in the aerospace industry because in these applications materials must be resistant to high temperature and abrasion.

3.2 Types of matrices

The matrices used are metals with low density and that the composites have high specific properties file. Thus the metals used are: aluminum, magnesium and titanium. Magnesium and aluminum have lower densities than polymeric matrices.

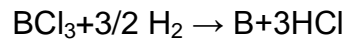
- Aluminum is the most commonly used metal because it is lighter and cheaper than the magnesium and titanium. Their oxidation behavior is better than that of magnesium as the surface is oxidized and the oxide is so compact that prevents progressing oxidation (passivation).
- Titanium has a density greater than that of magnesium and aluminum but its high melting temperature allows use at higher temperatures. Its main disadvantage is price.
- Magnesium is known for being the lowest density. Their mechanical properties are good but it must be protected against oxidation.

3.3 Types of reinforcing fibers

- Boron continuous fibers

The fiber of boron is a very hard material with a very high melting temperature.

It is obtained by CVD (Chemical Vapor Deposition): A tungsten wire is electrically heated in a hydrogen atmosphere and is brought into contact with boron trichloride, so that this compound is decomposed and boron is deposited on the wire.



To obtain the first composite material is due to impregnate the reinforcement with the metal matrix and it is carried out hot compression of the fibers between two sheets of metal. Subsequently, the material is laminated to obtain structures.

The factors to be controlled are the temperature and pressure to prevent rupture of the work piece and the presence of porosities.

The metal matrix composite materials and boron fibers are characterized by high modulus and strength.

- Continuous fibers of silicon carbide

The silicon carbide fiber is also obtained by chemical vapor deposition on a carbon substrate.

The fibers are impregnated by spraying the metal matrix on the fiber wound on a rotating drum. Subsequently, the sheet is molded by various techniques, for example, autoclave molding.

The main advantage of the continuous fiber metal matrix of silicon carbide is to adhere more readily to metal and its price is lower.

- Metal matrix composites with continuous fibers of graphite

The precursors are produced by the process of infiltration of liquid material. Graphite filaments are activated by chemical vapor deposition of a series of compounds and are wetted with aluminum or magnesium alloys. The composite fibers thus produced are laminated.

Different methods of manufacturing the composite material:

- Adhesion-diffusion: a camera is used in which the sheets are heated to the appropriate temperature and subjected to vacuum.
- Pultrusion: Consists of a hot isothermal process resulting geometry profiles determined by consolidation and adhesion of the sheets.
- Rapid-press process: The blades consolidate and adhere to a hot rolling process.
- Casting process: The reinforcing fibers are placed in a casting mold and molten metal is added. It is suitable for complex parts but not thin.

4. Ceramics Matrix Composites

4.1 Introduction

- Ceramic matrices include those non-metallic inorganic solids. Are classified as:

- a) Glass: amorphous silicates are

- b) traditional ceramic materials: based on silicates, are used in manufacturing pottery products and cement.

- c) New ceramic materials: they are the most commonly used in composite materials.

- Compounds based on oxides and carbides among them:

- Alumina (Al_2O_3) which is obtained from bauxite, and is characterized by its good mechanical properties

- Silicon carbide (SiC), which is obtained from sand and coke (has lower density than the alumina).

- Ceramic materials are characterized by the following properties:

- Resist high temperatures, so that can be used as refractory materials (materials that can withstand extremely high temperatures without losing its strength),

- They have high compressive strength but not in traction.

- Important aspects to consider in these materials are the different thermal expansion coefficients of fiber and matrix.

- If the coefficient of expansion of the matrix is greater than that of the fibers, breakage can occur in the matrix during cooling.

- If the coefficient of expansion of the array is less than that of the fibers decreases the fiber-matrix adhesion because the fibers shrink.

4.2 Types of fibers

a. Metal fibers

When choosing a metal must be taken into account chemical compatibility with the ceramic matrix and the coefficient of expansion.

The use of metal fibers has the following disadvantages

- Ease of oxidation
- High density (compared to glass fiber and carbon), leading to low values of specific strength and modulus.

The main advantage of this booster is that it increases the resistance to thermal shock (cracking as a result of rapid temperature change).

b. Carbon fibers

The use of carbon fiber enhances the rigidity, strength and fracture energy of the material.

Have low density and withstand high temperatures in inert atmosphere, however, are easily oxidized in the presence of oxygen.

c. Ceramic fibers

The fiber most commonly used is silicon carbide (SiC). These fibers have better oxidation resistance than the metal and carbon fiber.

4.3 Process for obtaining a composite material: sintered

In sintering, the matrix in the form of dust and fibers are mixed and hot pressed to produce composite materials with low porosity. Lets make large pieces of small series but not very complex geometry.

a. Preparation of raw material

At this stage the material is powdered and can be carried out by mechanical or chemical methods.

Mechanical methods

Initially the material is crushed and pulverized with the aim of obtaining a material in fine powder form with a controlled particle size.

Grinding is accomplished by crushing and grinding mills which operate by impact, compression and friction, reducing the size of large blocks of departure.

The blocks obtained in the grinding phase is pulverized by the grinding process. In grinding, the predominant mechanisms are impact and abrasion, acting on the movement of half hard and free (beads, stones, rods) on which the material interacts.

In mechanical methods of grinding elements can contaminate the material.

Chemical methods

Chemical methods are more complex but provide greater uniformity and quality of the powder. The two methods used are:

- Freeze-drying: is part of a salt of the raw material is dissolved in water. This solution is sprayed into small droplets that freeze quickly, and are dried in vacuum chambers. Subsequently, the salt is thermally decomposed giving rise to fine particles of ceramic material particles.

- Precipitation of a solution: the raw material is dissolved in water and filtered to remove impurities. Subsequently, the precipitation of the material in the form of intermediate, which results in the ceramic material by thermal decomposition.

Takes place after mixing the various components and additives comprising the molding material.

b. Molding

In this phase are mixed with the components and additives comprising the molding material and gives the material the desired shape. Can be carried out by different methods:

- Molded slider: it takes a very smooth paste to flow and fill the mold properly without causing defects due to lack of filling.
- Cold isostatic pressing: is carried out with fluid pressure and molded rubber.
- Hot Isostatic Pressing: is carried out with gas pressure and sheet metal molds.

c. Sintering

It is a heat treatment operation is performed on the molded part to bond the particles and increase its mechanical strength. Subsequently, the finish is carried out using starting material of high hardness material using abrasives.

5. Nanocomposites

5.1 Introduction

Traditional composite materials have several limitations such as low ductility. To overcome these limitations are being developed nanocomposites.

The nanocomposites are composite materials in which at least one dimension of the particles dispersed in the polymeric matrix has dimensions in the nanometer (10^{-9} m). The small dimensions of the particles lead to a high interfacial area.

Several types of nanocomposites, depending on how many dimensions of the particles are in the nanometer range:

- a) If the three dimensions in the nanometer, there are nanoparticles.
- b) Two dimensions on the nanometer scale and the third largest: nanotubes.
- c) A single dimension in the nanometer range: nanosheets.

5.2 Nanoparticles

Nanoparticles are the most commonly used layered silicates also called clay. Its structure consists of two layers formed by tetrahedrons of aluminum oxide and a layer of silicon oxide octahedral. These layers form stacks with a regular spacing between them called the gallery. The silicate used is more montmorillonite. Some aluminum atoms (Al^{+3}) are replaced by Mg^{+2} , so that these clays are negatively charged surface named cationic exchange capacity is expressed as meq/100g. For electrical neutrality, the galleries containing cations Na^{+} and K^{+} .

These clays do not disperse readily in most polymers because they tend to agglomerate. Therefore, coupling agents are used, which are molecules with a hydrophilic group (with affinity for water) and a hydrophobic group (with affinity for the polymer).

There are different types of coupling agents and the most used are alkylammonium salts ($CH_3-(CH_2)_n-NH_3^{+}$).

These molecules are exchanged for Na^{+} or K^{+} and organosilicates obtained.

These organosilicates give rise to two effects:

- Enhance compatibility between the polymer and clay as they increase the hydrophobicity of silicate
- Increases the separation between sheets

Both effects increase the compatibility with the organic polymer, the facilitating the penetration of the polymer.

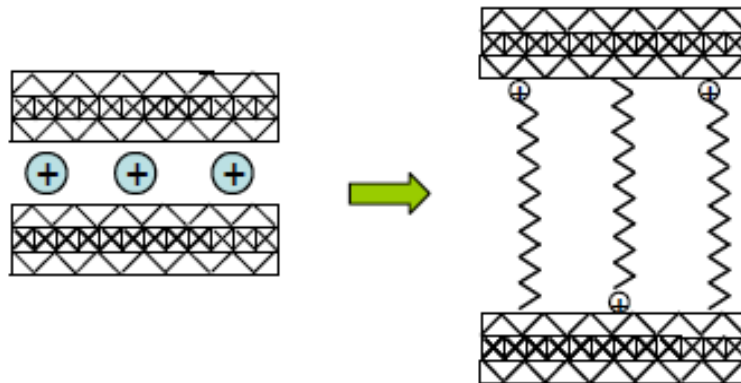


Figure 11. Nano- particles (Google images)

5.3 Nanocomposite structure

You can get three types of composite structures:

a) Microcomposite

The polymer enters the gallery and you get a composite phase separated microcomposite also called traditional or composite.

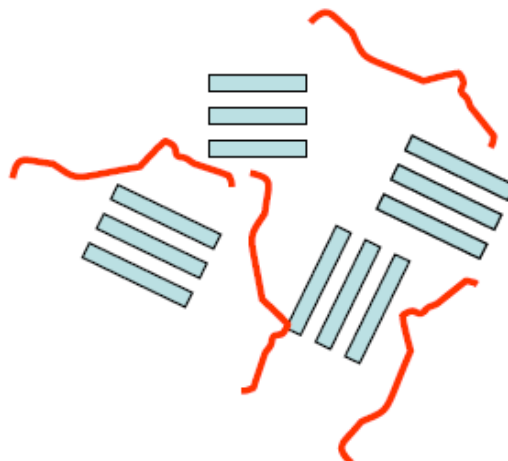


Figure 12. Microcomposite (Google images)

b) Intercalated nanocomposite

Polymer chains are inserted into the galleries between the sheets of silicates, resulting in a highly ordered multilayer morphology in alternating and inorganic polymeric sheets.

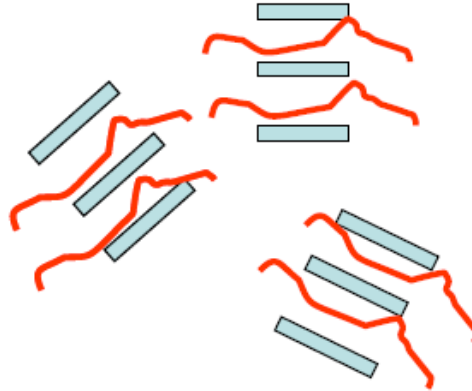


Figure 13. Intercalated nanocomposite (Google images)

c) Exfoliated nanocomposite

Silicates sheets 1 nm thick are uniformly dispersed in the polymer matrix. The large increase in polymer-clay surface area facilitates the transfer of charge from the array to nano-reinforcement, improving the mechanical properties.

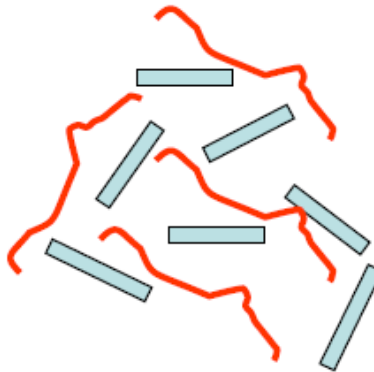


Figure 14. Exfoliated nanocomposite (Google images)

The main characterization techniques include X-ray diffraction and electron microscopy.

5.4 Techniques for preparing nanocomposites

a) Polymerization in-situ

It was the first method used and currently is the most widely used process.

In this technique the silicate is incorporated into a solution of monomer and polymerization is initiated.

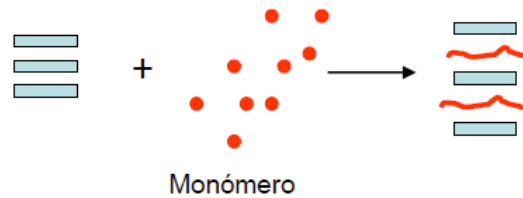


Figure 15. Polymerization in-situ (Google images)

b) In solution

The modified silicate is suspended in a polar organic solvent, and adding the dissolved polymer. Once it is achieved that the polymer chains are interleaved between layers of silicate. In a last step, the solvent was removed by evaporation under vacuum to obtain the nanocomposite.

The disadvantage of this technique is that it is difficult to implement on an industrial scale because of the problem of using large amounts of solvent.

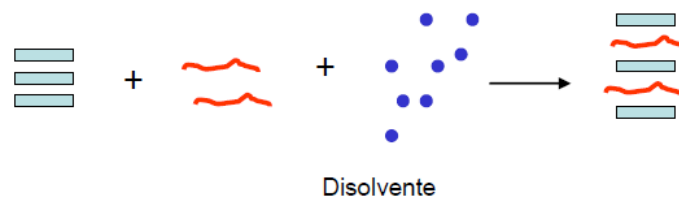


Figure 16. Polymerization in solution (Google images)

c) Collation melt

Involves melting the polymer and mixing with the silicate modified.

The advantages of this technique are that it requires no solvents and that the materials can be processed by simple techniques such as injection or extrusion.

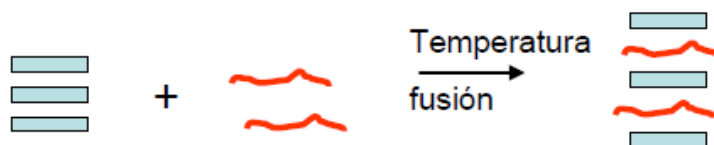


Figure 17. Polymerization collation melt (Google images)

5.5 Properties of the nanocomposites

a) Mechanical properties

Nanocomposites produced a significant increase in mechanical properties with a small proportion of reinforcement. Its good mechanical properties and dimensional stability allows its use in construction. Moreover, their densities are less than that of conventional composites and therefore are less harmful to the environment.

b) Properties barrier

The incorporation of nanosheets decreases the permeability of the materials restricts the mobility of polymer chains. Moreover, the zigzag arrangement of the clay sheets, assume a tortuous path, which is reflected in a significant increase in barrier properties. This decrease in permeability allows the use of nanocomposites in wrapping and packaging polymer.

c) Thermal properties

- Thermal stability: the nanocomposite has higher thermal stability than the microcomposites because polymer chains are confined between the plates.

- Softening temperature under load: The nanocomposites allow achieving increases of up to 100 ° C in the temperature of deformation under load, thus broadening the applicability of the composites at higher temperatures (eg, car hood).

- Flammability: nanocomposites give rise to the formation of a carbonaceous layer which improves the burning behavior.

d) Optical properties

Transparent reinforced materials are obtained as the particles are so small that they cannot scatter light.

6. Mechanical behavior of materials

6.1 Introduction anisotropic elastic behavior

To study the mechanical behavior of composite materials must follow the following steps:

6.1.1. Elastic Problem

6.1.2. Behavioral relationship

6.1.3. Constitutive equations

6.1.4. Material symmetries

6.1.5. Orthotropic materials

6.1.6. Prints

6.1.1. Elastic Problem

The elastic problem is to determine the displacement field, the stress tensor and deformation tensor, to be known external forces or external actions, by the equilibrium, constitutive and compatibility equations.

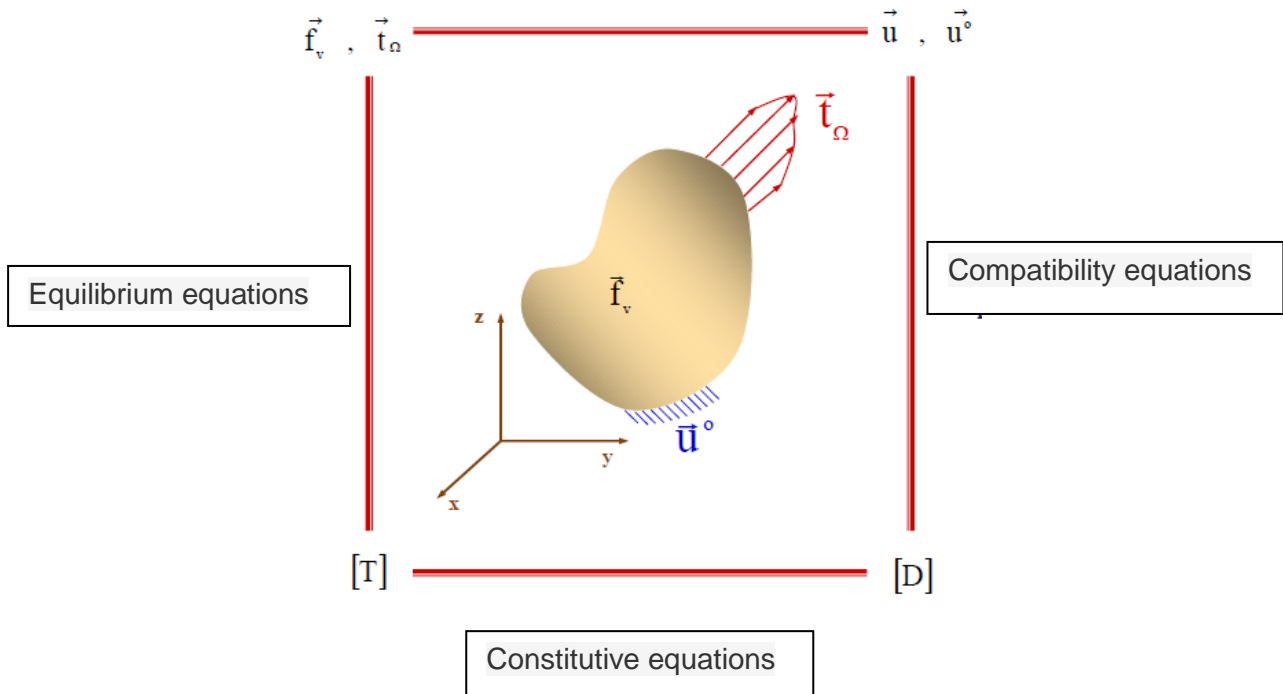


Figure 18. Elastic problem (Google images)

6.1.2. Behavioral relationship

The stress tensor in general depends on movement, time and temperature. But if we consider the type of material we can find simpler relations, for example:

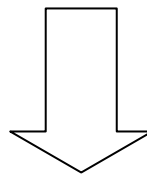
Type of material	Relationship
Viscoelastic	It is linear
linear elastic	It is independent of the time
Hyperelastic	$\frac{\partial U}{\partial \varepsilon_{ij}} = \sigma_{ij}$
Hipoelastic	$\frac{\partial \sigma_{ij}}{\partial t} = C \cdot \frac{\partial \varepsilon_{ij}}{\partial t}$

Table 5. Behavioral relationship

6.1.3. Constitutive equations

In linear elastic materials the more general relationship between deformation and stress Duhamel-Neumann :

$$\sigma_{ij} = (\sigma_{ij})^0 + C_{ijkl} \cdot (\varepsilon_{kl} - \varepsilon_{kl}^0) - \gamma_{ij} \cdot (\theta - \theta^0)$$



$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{12} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{13} & C_{23} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{14} & C_{24} & C_{34} & C_{44} & C_{45} & C_{46} \\ C_{15} & C_{25} & C_{35} & C_{45} & C_{55} & C_{56} \\ C_{16} & C_{26} & C_{36} & C_{46} & C_{56} & C_{66} \end{bmatrix} \cdot \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz}/2 \\ \gamma_{xz}/2 \\ \gamma_{xy}/2 \end{bmatrix}$$

Equation 2

Or the inverse tensor:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz}/2 \\ \gamma_{zx}/2 \\ \gamma_{xy}/2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{12} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{13} & S_{23} & S_{33} & S_{34} & S_{35} & S_{36} \\ S_{14} & S_{24} & S_{34} & S_{44} & S_{45} & S_{46} \\ S_{15} & S_{25} & S_{35} & S_{45} & S_{55} & S_{56} \\ S_{16} & S_{26} & S_{36} & S_{46} & S_{56} & S_{66} \end{bmatrix} \cdot \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{zx} \\ \tau_{xy} \end{bmatrix}$$

Equation 3

The tensor [C] is symmetric. Anisotropic material, which it is completely independent elastic, requires 21 constants.

6.1.4. Material symmetries

A plane of symmetry means that the elastic behavior of the material is the same in the two directions perpendicular to the plane.

Type of material	Planes of symmetry	Number of constant	Relationship
monoclinic symmetry	1	13	$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & C_{16} \\ C_{12} & C_{22} & C_{23} & 0 & 0 & C_{26} \\ C_{13} & C_{23} & C_{33} & 0 & 0 & C_{36} \\ 0 & 0 & 0 & C_{44} & C_{45} & 0 \\ 0 & 0 & 0 & C_{45} & C_{55} & 0 \\ C_{16} & C_{26} & C_{36} & 0 & 0 & C_{66} \end{bmatrix} \cdot \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \gamma_{yz}/2 \\ \gamma_{xz}/2 \\ \gamma_{xy}/2 \end{bmatrix}$
orthotropic symmetry	3	9	$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \cdot \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \gamma_{yz}/2 \\ \gamma_{xz}/2 \\ \gamma_{xy}/2 \end{bmatrix}$
transversely isotropic	3	5	$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{11} - C_{12} \end{bmatrix} \cdot \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \gamma_{yz}/2 \\ \gamma_{xz}/2 \\ \gamma_{xy}/2 \end{bmatrix}$
isotropic	3	2	$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{12} & 0 & 0 & 0 \\ C_{12} & C_{12} & C_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{11} - C_{12} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{11} - C_{12} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{11} - C_{12} \end{bmatrix} \cdot \begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \gamma_{yz}/2 \\ \gamma_{xz}/2 \\ \gamma_{xy}/2 \end{bmatrix}$

Table 5. Material symmetries

6.1.5. Orthotropic materials

An orthotropic material has two or three mutually orthogonal twofold axes of rotational symmetry so that its mechanical properties are, in general, different along each axis. Orthotropic materials are thus anisotropic; their properties depend on the direction in which they are measured.

For orthotropic material is observed experimentally that:

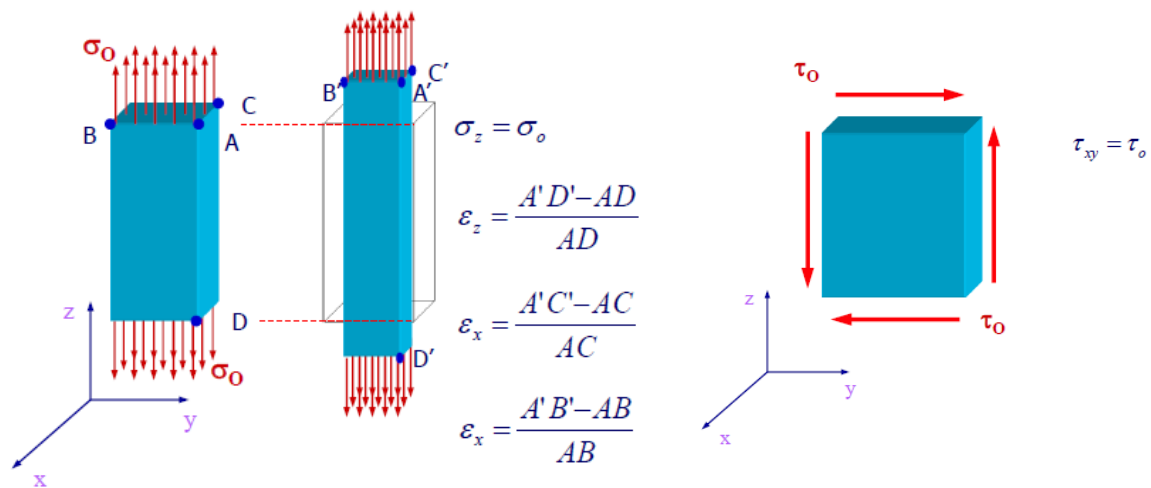


Figure 19. Orthotropic material (Google images)

Where we can apply:

-Hooke's law:

$$\varepsilon_z = \frac{\sigma_z}{E} \quad \gamma_{xy} = \frac{\tau_{xy}}{G}$$

Equation 4

-Poisson effect

$$\begin{aligned} \varepsilon_x < 0 \\ \varepsilon_x &= -\nu \cdot \varepsilon_z \\ \varepsilon_y < 0 \\ \varepsilon_y &= -\nu \cdot \varepsilon_z \end{aligned}$$

Equation 5

Where:

E → Young's modulus

ν → Poisson's modulus

G → Shear modulus

Then, we can calculate:

$$\begin{aligned}\varepsilon_1 &= \frac{\sigma_1}{E_1} - \frac{\nu_{12}}{E_2} \cdot \sigma_2 - \frac{\nu_{13}}{E_3} \cdot \sigma_3 & \gamma_{12} &= \frac{\tau_{12}}{G_{12}} \\ \varepsilon_2 &= \frac{\sigma_2}{E_2} - \frac{\nu_{21}}{E_1} \cdot \sigma_1 - \frac{\nu_{23}}{E_3} \cdot \sigma_3 & \gamma_{13} &= \frac{\tau_{13}}{G_{13}} \\ \varepsilon_3 &= \frac{\sigma_3}{E_3} - \frac{\nu_{31}}{E_1} \cdot \sigma_1 - \frac{\nu_{32}}{E_2} \cdot \sigma_2 & \gamma_{23} &= \frac{\tau_{23}}{G_{23}}\end{aligned}$$

Ecuación 6

6.1.6. Sheets

In sheets is a flat deformation state, therefore the constitutive equations are:

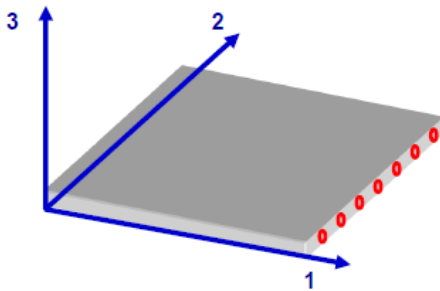


Figure 20. Sheets

$$\begin{aligned}\varepsilon_1 &= \frac{\sigma_1}{E_1} - \frac{\nu_{12}}{E_2} \cdot \sigma_2 \\ \varepsilon_2 &= \frac{\sigma_2}{E_2} - \frac{\nu_{21}}{E_1} \cdot \sigma_1 \\ \gamma_{12} &= \frac{\tau_{12}}{G_{12}}\end{aligned}$$

Equation 7

6.2 Sheet micromechanics

Micromechanics of the sheet is to study the behavior of the film considering the interactions of the constituent materials. Without considering separately the properties of the fibers and matrices, but the properties of the sheet.

Basic features of the sheets are:

- Volumetric content of reinforcement:

$$V_f = \frac{\text{Fibers volume}}{\text{total volume}}$$

$$V_m = \frac{\text{Matrix volume}}{\text{total volume}}$$

$$V_f + V_m = 1$$

Equation 8

- Mass content of reinforcement

$$M_f = \frac{\text{Fibers mass}}{\text{total mass}}$$

$$M_m = \frac{\text{Matrix mass}}{\text{total mass}}$$

$$M_f + M_m = 1$$

Equation 9

- Relationship V_f y M_f

$$V_f = \frac{M_f / \rho_f}{M_f / \rho_f + M_m / \rho_m}$$

Equation 10

$$M_f = \frac{V_f \cdot \rho_f}{V_f \cdot \rho_f + V_m \cdot \rho_m}$$

Equation 11

- Density of the compound.

To calculate the density of the compound (ρ) using the rule of mixtures

$$\rho = \rho_f \cdot V_f + \rho_m \cdot V_m$$

Equation 12

- Level of porosity: $V_{poros} \% = \frac{\rho_{teo} - \rho_{exp}}{\rho_{teo}} \times 100$

$\rho_{teo} \rightarrow$ Theoretical density

$\rho_{exp} \rightarrow$ Experimental density

Equation 13

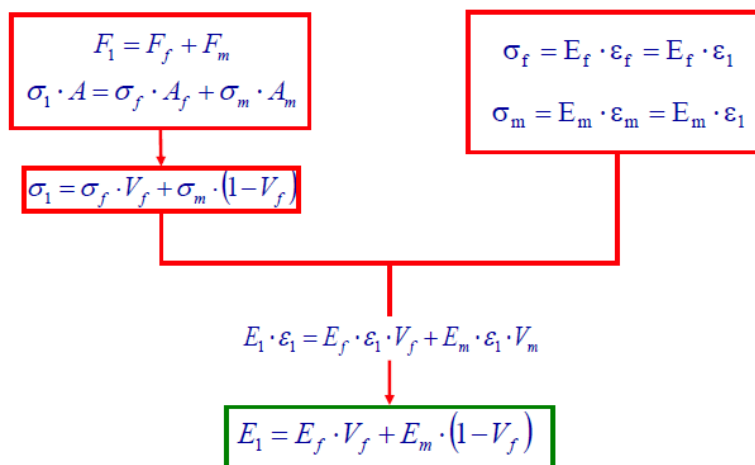
Unidirectional laminated Micromechanics

Hypothesis in the sheet material

- Macroscopically homogeneous
- Linear Elastic
- Macroscopically orthotropic
- Lack of initial stresses
- Union perfect fiber-matrix
- Absence of porosity

Calculate:

- E_1 :



Equation 14

- E_2 :

$$(1) \left\{ \begin{array}{l} \varepsilon_2 = \frac{\Delta w}{w} \quad \varepsilon_{2_f} = \frac{\Delta w_f}{w_f} \quad \varepsilon_{2_m} = \frac{\Delta w_m}{w_m} \\ \varepsilon_2 \cdot W = \varepsilon_{2_f} \cdot W_f + \varepsilon_{2_m} \cdot W_m \\ \varepsilon_2 = \varepsilon_{2_f} \cdot \frac{W_f}{W} + \varepsilon_{2_m} \cdot \frac{W_m}{W} \\ \varepsilon_2 = \varepsilon_{2_f} \cdot V_f + \varepsilon_{2_m} \cdot V_m \end{array} \right.$$

$$(2) \left\{ \begin{array}{l} \varepsilon_2 = \frac{\sigma_2}{E_2} \quad \varepsilon_{2_f} = \frac{\sigma_2}{E_{2_f}} \quad \varepsilon_{2_m} = \frac{\sigma_2}{E_{2_m}} \\ \sigma_2 = E_2 \cdot \varepsilon_2 = E_2 \cdot \left(\frac{\sigma_2}{E_f} \cdot V_f + \frac{\sigma_2}{E_m} \cdot V_m \right) \end{array} \right.$$

(1) and (2) \rightarrow

$$E_2 = E_m \left(\frac{1}{(1 - V_f) + \frac{E_m}{E_f} V_f} \right)$$

Equation 15

- V_{12} :

$$\begin{array}{c} \boxed{v_{21} = -\frac{\varepsilon_2}{\varepsilon_1}} \\ \downarrow \\ \boxed{\varepsilon_2 = \varepsilon_{2_f} \cdot V_f + \varepsilon_{2_m} \cdot (1 - V_f)} \\ \downarrow \\ \boxed{v_f = -\frac{\varepsilon_{2_f}}{\varepsilon_1} \quad v_m = -\frac{\varepsilon_{2_m}}{\varepsilon_1}} \\ \downarrow \\ \boxed{v_{21} = v_f \cdot V_f + v_m \cdot (1 - V_f)} \end{array}$$

Equation 16

- G_{12} : Equation Halpin-Tsai:

$$G_{12} = E_m \cdot \frac{1 + \xi_1 \cdot \eta_1 \cdot V_f}{1 - \eta_1 \cdot V_f}$$

$$\eta_1 = \frac{G_f - G_m}{G_f + \xi_1 \cdot G_m}$$

$$\xi_1 = 1$$

Equation 17

6.3 Breaking issues film micromechanical

6.3.1 Failure modes

High V_f Low V_f

High V_f Low V_f

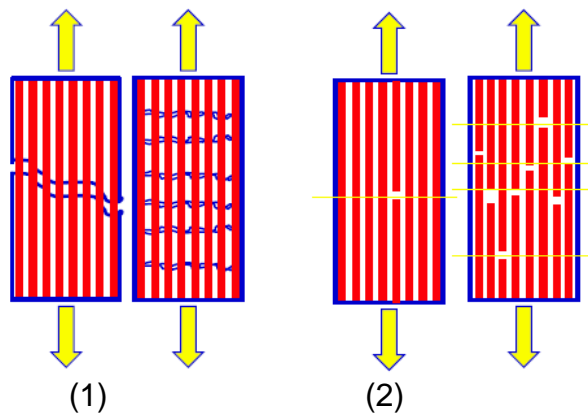


Figure 21. Failure modes

(1) Mode of failure by fracture of the matrix occurs in cases where the fiber strength is higher than that of the matrix.

(2) Mode of failure by fracture of the fiber, occurs in cases where the strength of the matrix is greater than that of the fibers.

6.3.2 Mechanical Tensile strength fiber direction

		fiber volume	maximum tension before breakdown
Deformation at break of the fiber lower than that of the matrix	$\epsilon_f^R < \epsilon_m^R$	High	$X_t = \sigma_f^R \cdot \left[V_f + \frac{E_m}{E_f} \cdot (1 - V_f) \right]$
		Low	$X_t = \sigma_m^R \cdot (1 - V_f)$
Deformation at break of the fiber higher than that of the matrix	$\epsilon_m^R < \epsilon_f^R$	High	$X_t = \sigma_f^R \cdot V_f$
		Low	$X_t = \sigma_m^R \cdot \left[V_f \cdot \frac{E_f}{E_m} + (1 - V_f) \right]$

Table 6. Mechanical Tensile strength fiber direction

All the above results do not take into account the statistical distribution of the tensile strengths of fiber and matrix.

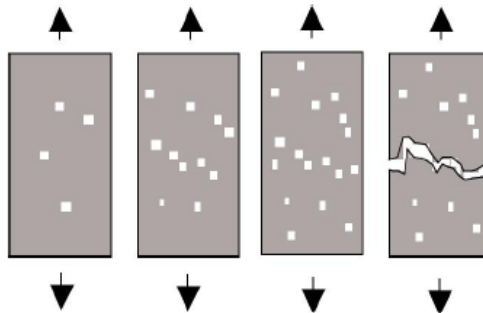


Figure 22. Statistical distribution of the tensile strengths

6.3.3 Mechanical Compression strength in fiber direction

Failure modes in compression in fiber direction:

- Microbuckling of the fibers:

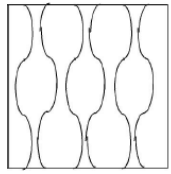
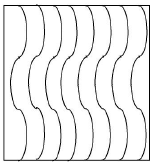
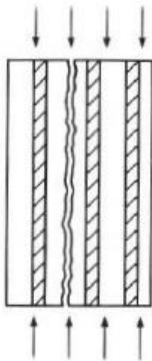
Specific volume of fibers	Mode	X_c
Low	 <p>↑ extensional mode</p>	$X_c = 2 \cdot V_f \cdot \sqrt{\frac{E_m \cdot E_f \cdot V_f}{3 \cdot (1 - V_f)}}$
High	 <p>↑ shear mode</p>	$X_c = \frac{G_m}{1 - V_f}$

Table 7. Types of microbuckling of the fibers

- Poisson effect of transverse rupture:



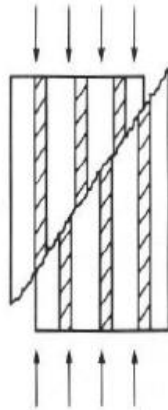
The fault occurs when the transverse tensile strain produced by Poisson effect, reaches a critical value (deformation at break-away)

$$X_c = \frac{(E_f \cdot V_f + E_m \cdot V_m) \cdot \left(1 - V_f^{1/3}\right)}{v_f \cdot V_f + v_m \cdot V_m} \cdot \epsilon_m^R$$

Equation 18

- Ultimate shear:

Appears frequently in films with a high fiber content, is governed by the shear failure of the fibers themselves



$$X_c = 2 \cdot S_f \cdot \left[V_f + (1 - V_f) \cdot \frac{E_m}{E_f} \right]$$

Equation 19

6.3.4 Mechanical Tensile strength in transverse direction

Thus biasing may be the most critical for attracting the low resistance of the resin. Occurs when loads acting in the transverse direction of the sheet, then stress concentrations occur in areas close to the matrix fibers (interfasefibra / matrix).

It depends on many factors:

- Properties of the fibers and matrix
- The interface resistance of fiber-matrix
- The presence and distribution of voids
- Internal distribution of stresses and strains

- If the union of the interface is weak:

$$Y_t = \sigma_m^R \cdot \left[1 - 2 \cdot \left(\frac{V_f}{\pi} \right)^{\frac{1}{2}} \right]$$

Equation 20

- If the union of the interface is strong:

$$Y_t = \frac{E_2 \cdot \sigma_m^R}{E_m \cdot F} \quad F = \frac{1}{\left(\frac{2 \cdot r}{R} \cdot \left(\frac{E_m}{E_{f_2}} - 1\right) + 1\right)}$$

Equation 21

6.3.5 Mechanical compression strength in the transverse direction

There are several mechanisms:

- Failure by shear of the matrix
- Failure by shear of the matrix with off fibramatriz
- Failure by crushing of the fibers

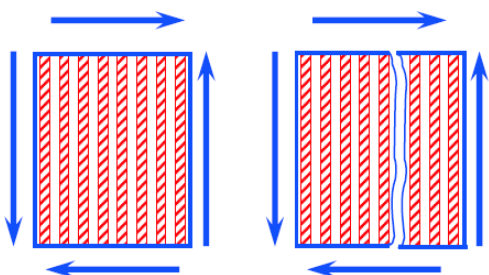
The failure occurs by shear in a plane parallel to the fibers in a direction perpendicular to them. The plane makes an angle of 45 ° to the loading direction

$$Y_c = E_2 \cdot \left[\frac{2 \cdot r}{R} \cdot \frac{E_m}{E_f} + \left(1 - \frac{2 \cdot r}{R}\right) \right] \cdot \varepsilon_m^R$$

Equation 23

6.3.6 Mechanical resistance to shear plane

Under these conditions appears a large stress concentration along the interface fiber / matrix. These stresses can cause failure by shear of the matrix and / or fiber-matrix off.



$$S = \frac{G_{12} \cdot \tau_m^R}{G_m \cdot F} \quad F = \frac{1}{\left(\frac{2 \cdot r}{R} \cdot \left(\frac{G_m}{G_f} - 1\right) + 1\right)}$$

Equation 24

6.4 Failure theory

Failure theory is the science of predicting the conditions under which solid materials fail under the action of external loads. The failure of a material is usually classified into brittle failure (fracture) or ductile failure (yield). Depending on the conditions (such as temperature, state of stress, loading rate) most materials can fail in a brittle or ductile manner or both. However, for most practical situations, a material may be classified as either brittle or ductile.

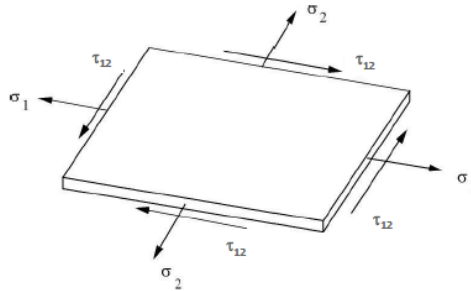


Figure 23. Failure theory

Some failures criterias are:

- Failure criteria uncoupled:

- Maximum tension:

$$(\sigma_I^2 - \sigma_e^2) \cdot (\sigma_{II}^2 - \sigma_e^2) \cdot (\sigma_{III}^2 - \sigma_e^2) \geq 0$$

Equation 25

- Maximum deformation:

$$(\varepsilon_I^2 - \varepsilon_e^2) \cdot (\varepsilon_{II}^2 - \varepsilon_e^2) \cdot (\varepsilon_{III}^2 - \varepsilon_e^2) \geq 0$$

Equation 26

- Failure criteria with interaction:

- Tsai Hill

$$\frac{1}{X^2} \sigma_1^2 + \frac{1}{Y^2} \sigma_2^2 + \frac{1}{Z^2} \sigma_3^2 - \left(\frac{1}{X^2} + \frac{1}{Y^2} - \frac{1}{Z^2} \right) \sigma_1 \sigma_2 - \left(\frac{1}{X^2} + \frac{1}{Z^2} - \frac{1}{Y^2} \right) \sigma_1 \sigma_3 - \left(\frac{1}{Y^2} + \frac{1}{Z^2} - \frac{1}{X^2} \right) \sigma_2 \sigma_3 + \frac{1}{S_{YZ}^2} \tau_{23}^2 + \frac{1}{S_{XZ}^2} \tau_{13}^2 + \frac{1}{S^2} \tau_{12}^2 = 1$$

Equation 27

- Hoftmann

$$F_1 \cdot \sigma_1 + F_2 \cdot \sigma_2 + F_{11} \cdot \sigma_1^2 + F_{22} \cdot \sigma_2^2 + F_{66} \cdot \tau_{12}^2 + 2 \cdot B_{12} \cdot \sigma_1 \cdot \sigma_2 = 1$$

Equation 28

where:

$$F_1 = \frac{1}{X_t} + \frac{1}{X_c} \quad F_2 = \frac{1}{Y_t} + \frac{1}{Y_c} \quad B_{12} = -\frac{1}{2 \cdot X_t \cdot X_c}$$

$$F_{11} = -\frac{1}{X_t X_c} \quad F_{22} = -\frac{1}{Y_t Y_c}$$

Equation 29

- Wu Tsai

$$F_1 \cdot \sigma_1 + F_2 \cdot \sigma_2 + F_6 \cdot \tau_{12} + F_{11} \cdot \sigma_1^2 + F_{22} \cdot \sigma_2^2 + F_{66} \cdot \tau_{12}^2 + 2 \cdot F_{12} \cdot \sigma_1 \cdot \sigma_2 = 1$$

Equation 30

Where:

$$F_1 = \frac{1}{X_t} + \frac{1}{X_c} \quad F_2 = \frac{1}{Y_t} + \frac{1}{Y_c} \quad F_{66} = \frac{1}{S^2}$$

$$F_{11} = -\frac{1}{X_t X_c} \quad F_{22} = -\frac{1}{Y_t Y_c} \quad 2 \cdot F_{12} = -\left(\frac{1}{\sigma_e}\right) \cdot \left(\frac{1}{\sigma_e}\right)$$

Equation 31

- Multiple failure criteria:

- Hann, Erikson & Tsai

Failure of fibers: $(F_{11} \cdot \sigma_1^2) + (F_1 \cdot \sigma_1) = 1$

Equation 32

Failure of matrix: $F_{22} \cdot \sigma_2^2 + F_{66} \cdot \tau_{12}^2 + F_{44} \cdot \tau_{13}^2 + F_{55} \cdot \tau_{23}^2 + F_2 \cdot \sigma_2 = 1$

Equation 33

- Hashin

Failure of fibers:

$$F_{11} \cdot \sigma_1^2 + F_{66} \cdot \tau_{12}^2 + F_1 \cdot \sigma_1 = 1$$

Equation 34

Failure of matrix:

$$F_{22} \cdot \sigma_2^2 + F_{66} \cdot \sigma_{12}^2 + F_{44} \cdot \tau_{13}^2 + F_{55} \cdot \tau_{23}^2 + F_2 \cdot \sigma_2 = 1$$

Equation 35

7. Effects of environment on mechanical behavior

A composite material can be exposed to various environments such as moist air, high temperature, low temperature, solar radiation, chemical attack, lightning, space environment .. which can change their mechanical behavior, the most important factors are: change of properties mechanical constituents, loss of fiber-matrix adhesion, occurrence of stresses associated with the differences in properties.

Effects of environment on mechanical behavior:

- Hygrothermal effects
- Solar radiation
- Space environment
- The ray
- Biological Effects
- Fire behavior
- Corrosion

7.1 Hygrothermal effects

Hygrothermal effects are due primarily to temperature and humidity to which the materials are subjected, but its effects also depends on other factors such as: type of matrix and fiber, exposure time and geometry of the component.

- Weight gain

Polymeric matrices absorb moisture until it reaches the saturation point:
Thermoset matrices: 1% -2% Thermoplastic matrices: 0.1% -0.3%

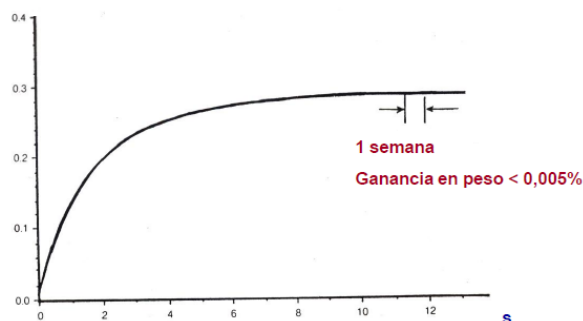


Figure 24. Typical equilibrium curve of a thermoplastic polymer (Google images)

- Swelling of the matrix

- Decrease in glass transition temperature (T_g) of the resin

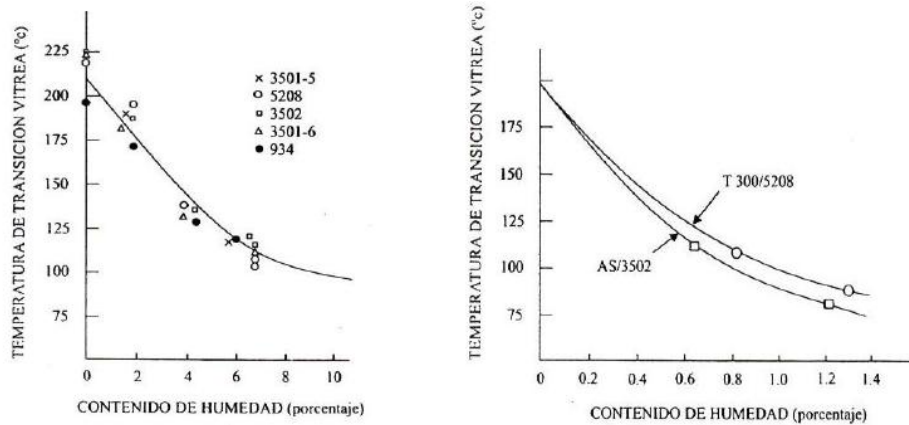


Figure 25. Glass transition temperature versus moisture content (Google images)

- Delamination of the material
- Blistering surface
- Chemical degradation

Overall, we conclude that: Warm, moist conditions cause an increase in ductility the matrix. Dry and cold environments increase the brittleness of the matrix Alternating cycles of wet and dry conditions stiffness losses arising mechanical joints.

Types of laminates	Moisture		Temperature	
	Mechanical strength	Modulus of elasticity	Mechanical strength	Modulus of elasticity
Unidirectional laminates in the longitudinal and quasi-isotropic	< 1% No change	No change	-40°C < T < 190°C No changed	-40°C < T < 230°C unchanged
	> 1% reduced		190 ° C < T decrease	
Unidirectional laminates in transverse direction	significantly decreases	significantly decreases	significantly decreases	significantly decreases

Table 8. Changes in the mechanical behavior of different sheets against temperature and humidity

Hygrothermal source voltages are associated with differences in coefficients of expansion (thermal and moisture) between fiber and matrix and / or between adjacent sheets with different orientation.

7.2 Solar radiation

Effects of infrared radiation and visible: not have enough energy to break bonds; its only effect is thermal.

Effects of ultraviolet radiation have enough energy to break bonds and initiate chemical reactions, and can therefore occur:

- Weight loss due to breakage of the polymer chain
- Appears porosity
- It generates internal stresses

For the polymers are affected by ultraviolet rather than metals or ceramics

	affected by UV	No- affected by UV
Fibers	Kevlar-29	carbon , Glass, Boron
Matrix	polyester	epoxy

Tabla 9. Materials affected by ultraviolet

7.3 Biological Effects

The biological effects mainly affect polymeric materials, by involving its degradation.

There are several methods of attack:

- Direct attack on the matrix: Microorganisms can produce acids or enzymes that destroy the polymer
- Blistering: It appears delaminating.
- Break through calcareous deposits: Forming particles of foreign material inside the laminate

7.4 The ray

The composite structures to be protected from the effect of ray. Protection systems most used are: aluminum mesh, aluminum layer, nickel-coated fibers, metal fibers embedded in the material, conductive paint, conductive bars and conductive polymers.

7.5 Space environment

The space environment is an environment in which the materials are subjected to heat shock, reaction with atomic oxygen, impact, degassing and radiation.

7.6 Fire behavior

We consider the following: Growth of fire, toxicity of the gases generated, residual strength and structural integrity and extinction of the flame.

The factors that control fire behavior:

- Matrix type
 - Fiber Type
 - Volume of fiber
 - Distribution of fibers
 - Content retardant additives
- Thermal effects on the carbon / epoxy function of temperature:

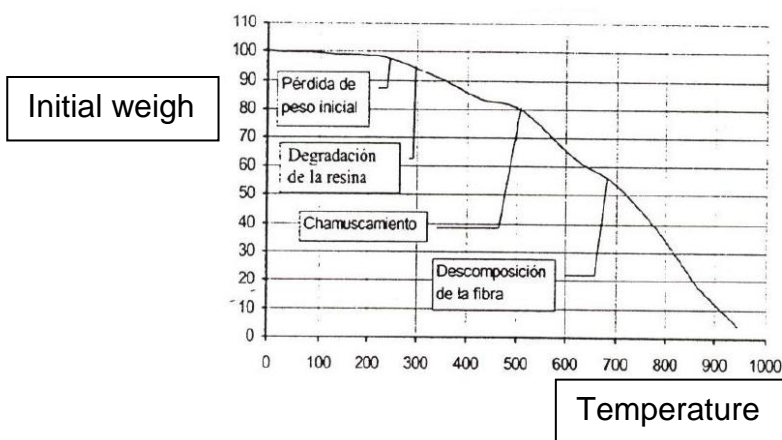


Figure 26. Thermal effects on the carbon / epoxy function of temperature (Google images)

- Thermal degradation of a material glass / phenolic resin

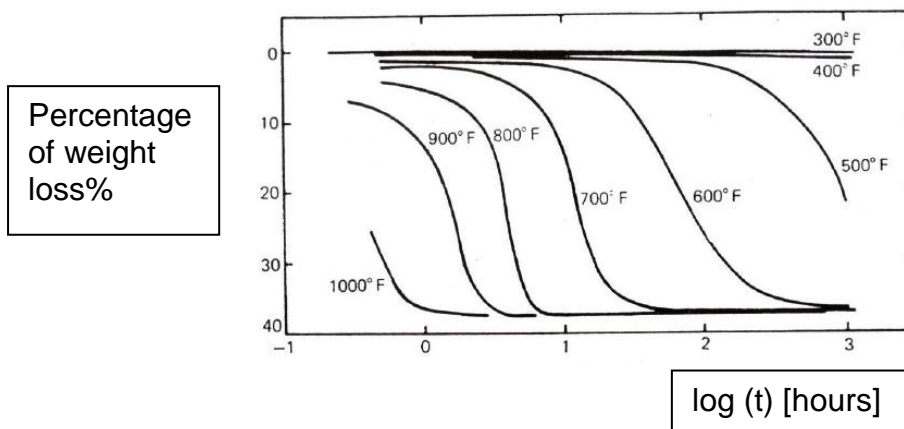


Figure 27. Thermal degradation of a material glass / phenolic resin (Google images)

- Inter-laminar shear strength depending on the temperature and time [min]

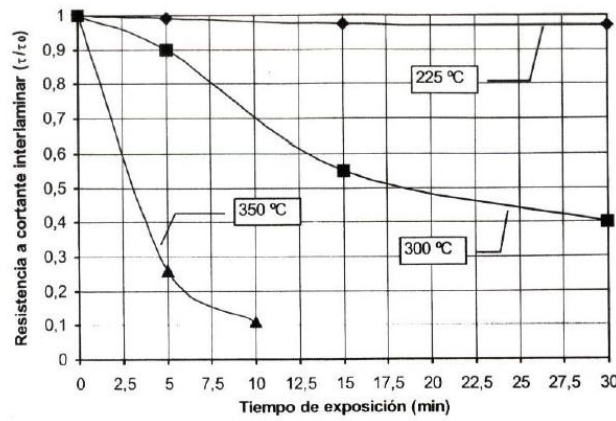


Figure 28. Inter-laminar shear strength depending on the temperature and time.

- Hardness in function of temperature and time

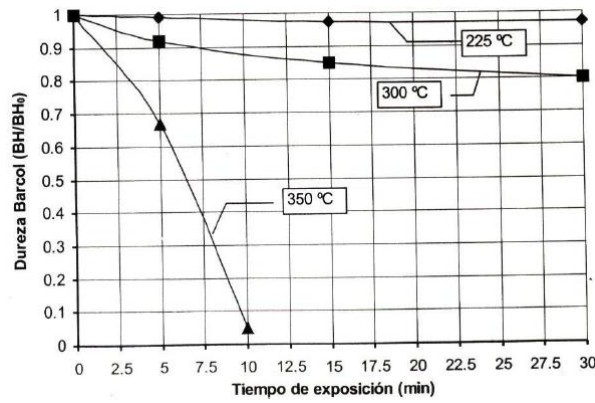


Figure 29. Hardness in function of temperature and time

- Flat shear strength depending on the temperature and time

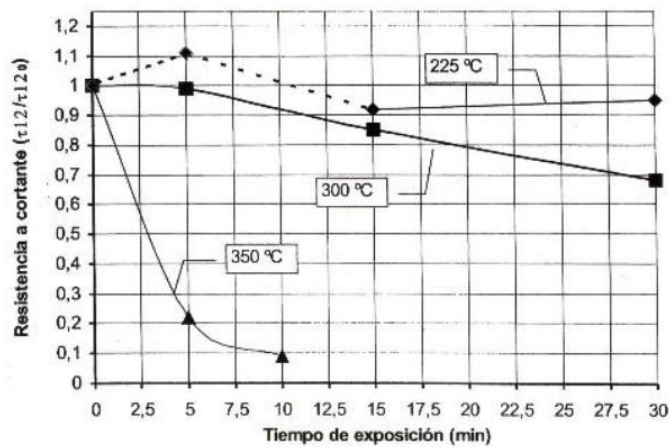


Figure 30. Flat shear strength depending on the temperature and time

The following methods slow down or reduce their effects:

- Resins intumescent
- Flame retardant resins
- Blankets of glass
- Ceramic fabrics
- Phenolic foams
- Flame retardants
- Aluminum hydroxide
- Antimony oxides

The polymer matrix composite materials can not meet the requirements on fire behavior

7.7 Chemical corrosion

Corrosion is the gradual destruction of material, usually metals, by chemical reaction with its environment.

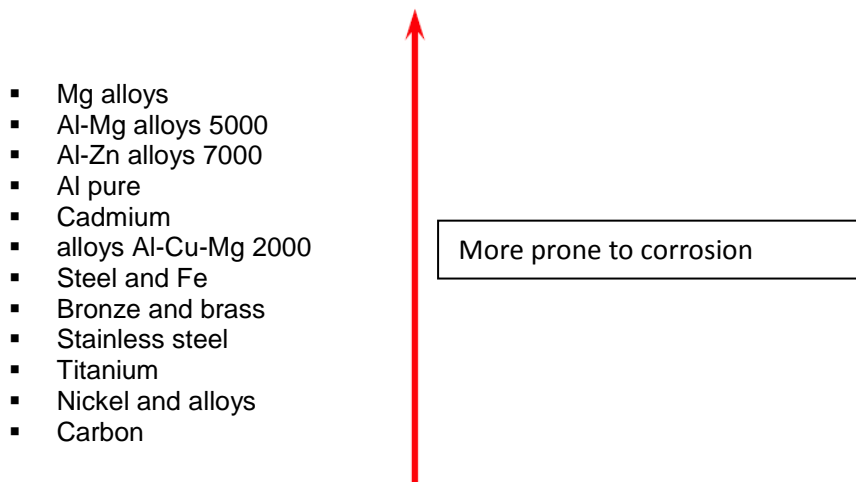
The polymeric matrix composites show a better behavior against corrosion of metals, in this case also the dominant factor is the matrix

- Galvanic corrosion

Galvanic corrosion occurs when two different metals have physical or electrical contact with each other and are immersed in a common electrolyte, or when the same metal is exposed to electrolyte with different concentrations. In a galvanic couple, the more active metal (the anode) corrodes at an accelerated rate and the more noble metal (the cathode) corrodes at a retarded rate. When immersed separately, each metal corrodes at its own rate. What type of metal(s) to use is readily determined by following the galvanic series.

Factors such as relative size of anode, types of metal, and operating conditions (temperature, humidity, salinity, etc.) affect galvanic corrosion. The surface area ratio of the anode and cathode directly affects the corrosion rates of the materials.

Appears in mechanical joints metal-composite material.



The following methods slow down or reduce their effects:

- Isolation of the contact surfaces
- Insulating paints
- Anodized metal element
- Use of corrosion resistant steels and titanium alloys

8. Summary

Composite materials are a little tool exploited in the area of construction.

Are the answers to engineering problems of great current interest because of the diversity of types that exist, their good mechanical properties and its versatility to adapt to different conditions that can be exposed (temperature, humidity, aggressive atmospheres). The problem we plated these materials are few studies and the few references we have of them as they are being used in a short time, but several hypotheses can know by far the performance, mechanical performance and service life .

For all of them can claim to be the materials of the future and a large field for investigation.

9. Bibliography

<http://ocw.ehu.es/enseñanzas-tecnicas/materiales-compuestos>

<http://ocw.uc3m.es/mecanica-de-medios-continuos-y-teoria-de-estructuras/mecanica-de-materiales-compuestos>

[Lomborg, Bjørn](#) (2001). *The Skeptical Environmentalist: Measuring the Real State of the World*. p. 138. [ISBN 978-0-521-80447-9](#).

[Minerals commodity summary – cement – 2007](#)". US [United States Geographic Service](#). 1 June 2007. Retrieved 16 January 2008.

David Hon and Nobuo Shiraishi, eds. (2001) Wood and cellulose chemistry, 2nd ed. (New York: Marcel Dekker), p. 5 ff.

Heather Lechtman and Linn Hobbs "Roman Concrete and the Roman Architectural Revolution", *Ceramics and Civilization Volume 3: High Technology Ceramics: Past, Present, Future*, edited by W.D. Kingery and published by the American Ceramics Society, 1986; and Vitruvius, Book II:v,1; Book V:xii2