Centro Stampa

N° 4343

DESIGN OF LIGHTINEIGHT AND COMPOSITE STRUCTURES
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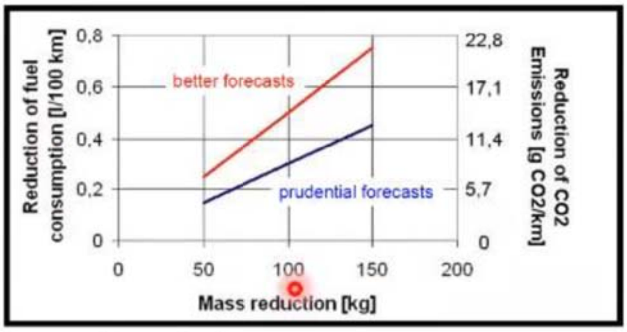
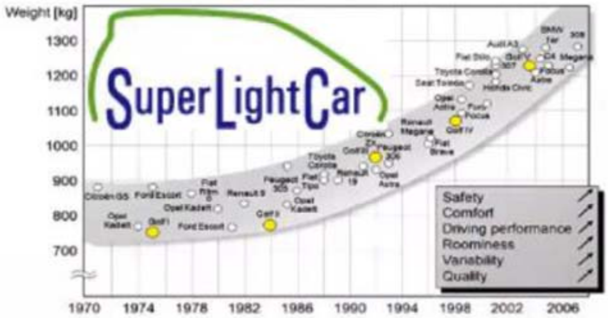
Introduction

We want lightweight structure because

- Increment of performance (fuel consumption, speed, payload), new regulations want the cars to be lighter
- Reduction of air pollution and emissions of greenhouse gasses



Expected outcomes from mass reduction



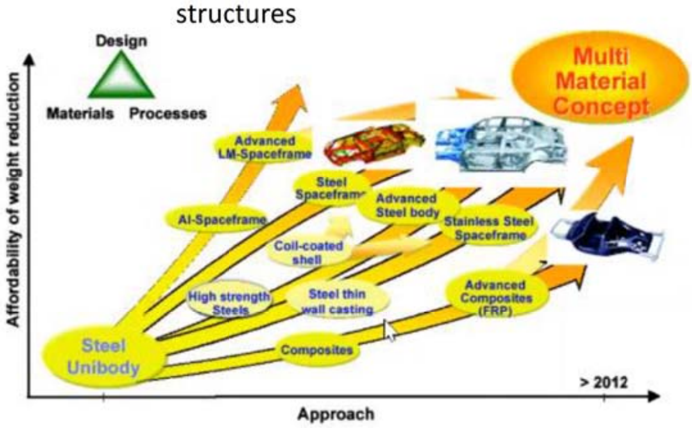
Weight of vehicles is continuously increasing to fulfil required targets

We all know the fuel cost increases, so a reduction of fuel consumption is very important.
Also, it is an important factor in vehicles but also for manufacturing, faster machines let us produce faster.
Lesser mass means that we can increase the payload.
An increase of efficiency lets us reduce the air pollutions.

These requests are in clear contrast with the general trend cars have been following in the past decades. Safety, comfort, driving performance, roominess, variety, and quality are all factors that consumers want and that require more mass.

How to lightweight

- Downsizing, we reduce the dimensions, roominess, so the total mass decreases, it's not optimal but it's a way
- Design optimization, by using additive manufacturing we have a new way to design components with topology optimisation where we add material only where it's needed
- Joining techniques, by using joints rather than bolts and other heavy components we can get a lighter structure
- Materials
  - Lighter materials (aluminium and magnesium alloys), the approach is the same as steel but with lighter materials
  - More performing materials (high strength steels), if we increase the performance of the metal, we can decrease the volume and so the mass
  - Lighter and more performing materials (fibre reinforced composites), they perform even better than high performance steels but are much lighter, so this is best option for lighter structures



Composites

Two or more chemically different constituents combined macroscopically (interface is clear) to yield a useful and new material.
The interface between the two materials must be clear, even nano composites, which aren't macroscopically combined, are indeed composites because the interface is clear.
A composite can be naturally occurring, such as wood, bone, and granite.
Examples of man-made composites are concrete, plywood and fibrous composites.

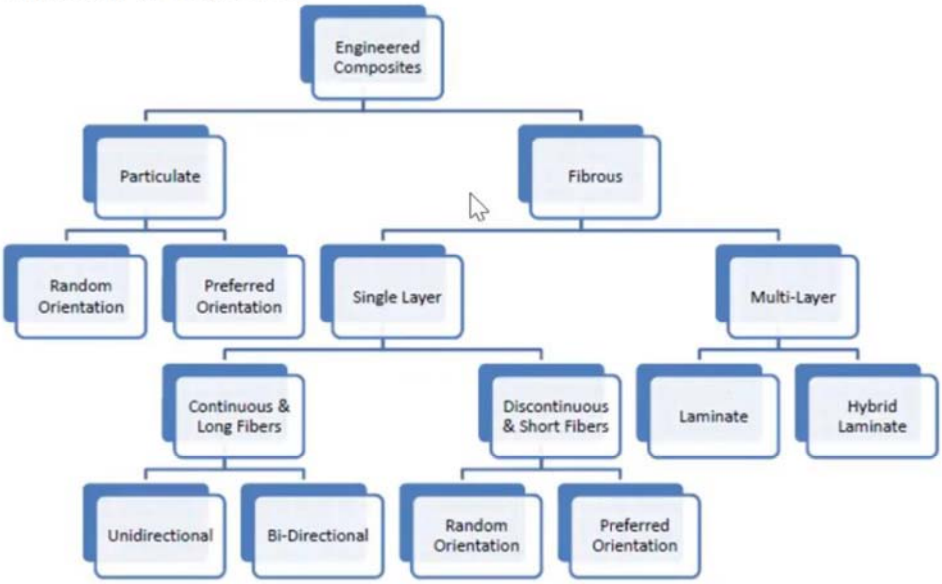
These are NOT composites

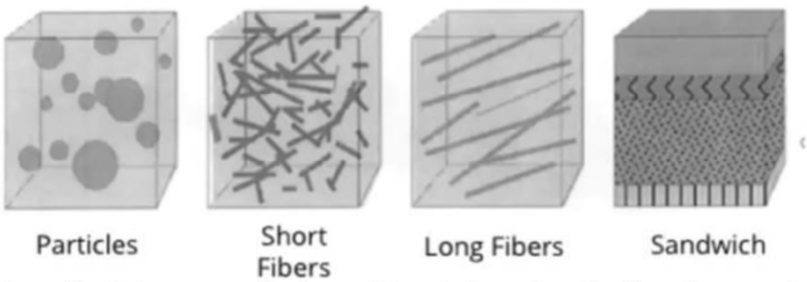
Plastics because even though they may have fillers their presence does not alter the physical properties significantly; alloys because they are macroscopically heterogeneous; metal with impurities because they don't alter the properties significantly.

Where are composites used

- Automotive industry, because they are lighter, stronger, wear resistance, rust free, aesthetic, and have good damping
  - Car body
  - Brake pads
  - Drive shafts
  - Fuel tanks
  - Hoods
  - Spoilers
- Aerospace because they are lighter, stronger, have temperature stability (having a thermal expansion coefficient that can even be zero), smart structures, wear resistance
  - Aircraft
  - Rockets and missiles
  - Satellites
- Sports, because they sport components can be lighter, stronger, tougher, better aesthetics, higher damping properties
  - Tennis
  - Bicycles
  - Badminton
  - Boats
  - Hockey
  - Golfing
  - Motorcycles
- Transportation and infrastructure because they are lighter, stronger, tougher, and have good damping
  - Railway coaches
  - Bridges
  - Ships and boats
  - Dams
  - Truck bodies and floors
  - RV bodies
- And many more industry sectors
  - Biomedical industry
  - Consumer goods
  - Agricultural equipment
  - Heavy machinery
  - Computes
  - Healthcare

Classification of composites



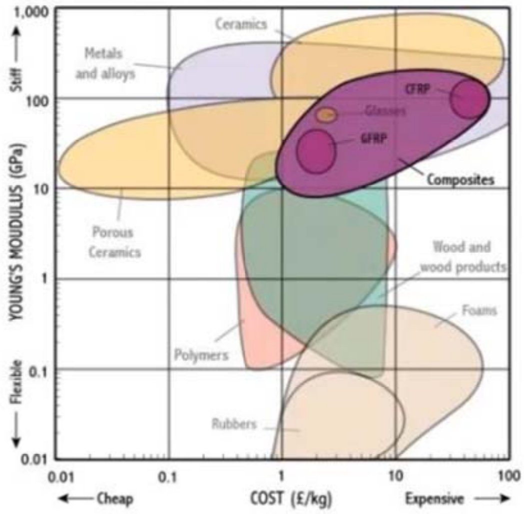


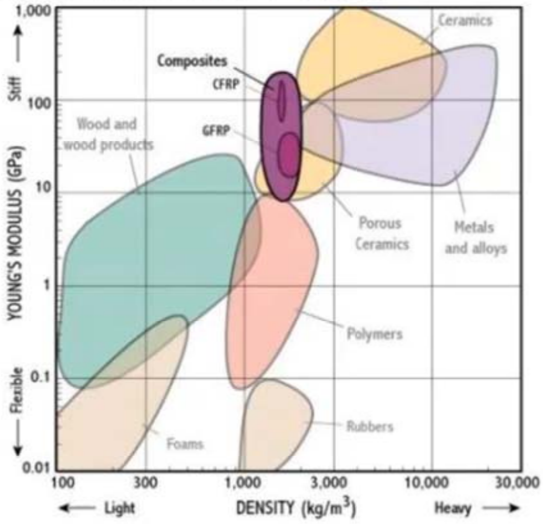
Generally particulate composite is used to reinforced synthetics, they can have random orientation or preferred orientation (we won't see them).
We will see *fibrous composites*

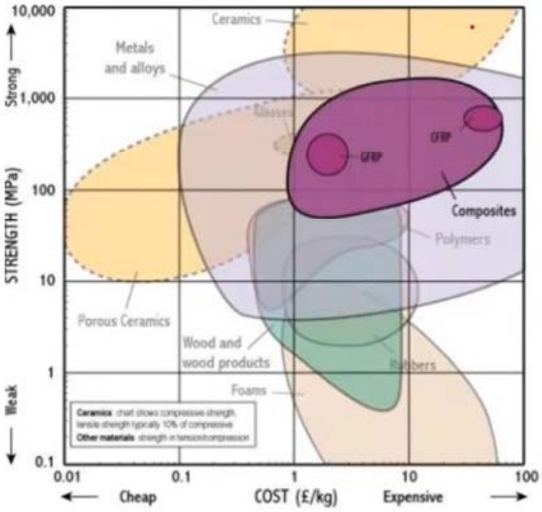
- Single layer fibrous composites (we need to know how this work so that we can study the multi layers), they have fibres of reinforcing materials suspended in binding matrix. Unlike particle, a fibre has high length to diameter ratio, and further its diameter may be close to its crystal size.
  - Continuous and long fibres, this yields to the best copositive properties
    - Unidirectional
    - Bi-directional
  - Discontinuous and short fibres, this is the trade-off that gives good enough structural properties but still better than the matrix material
    - Random orientation, means that we have isotropic behaviour
    - Preferred orientation
- Multi-layer fibrous composite's structure
  - Laminate, they are made of the laminate of the same material
  - Hybrid laminates are made of stack of laminate that are different materials. It changes the material properties layer by layer.

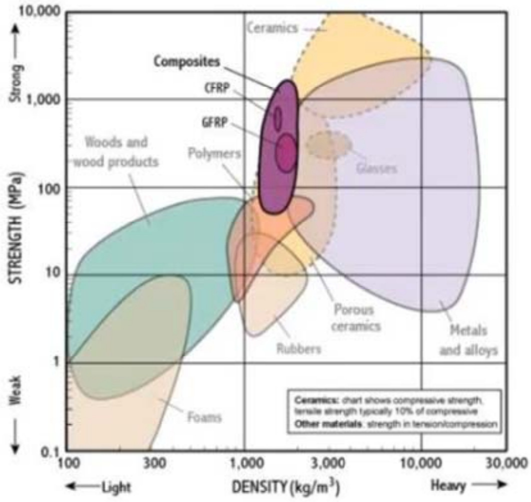
Ashby diagrams

Are a compact way to describe materials and they let us choose what materials to choose

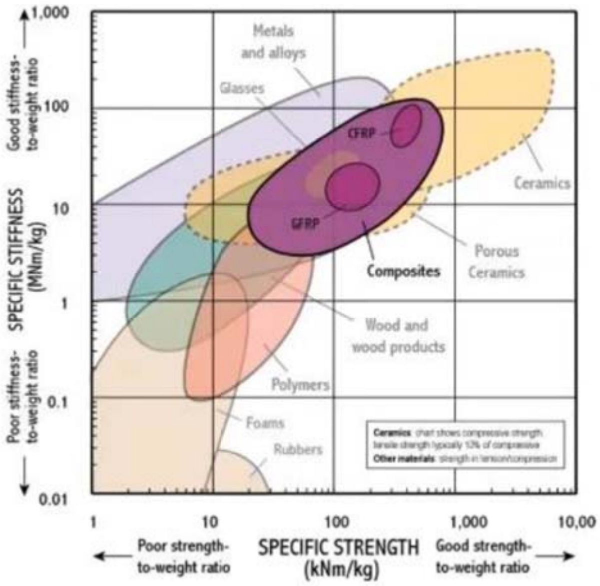


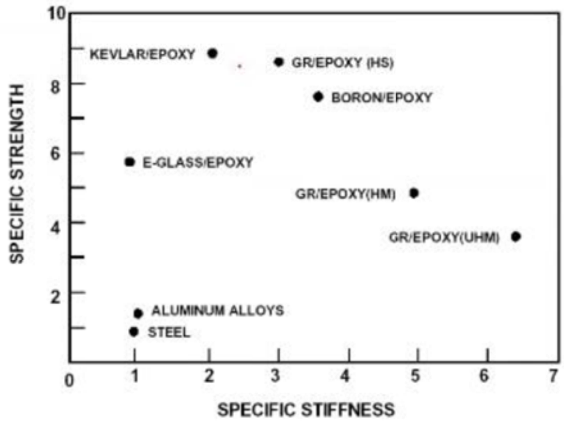






To highlight the fact that the strength is similar to metal, but the density is much lower we can compute the specific properties, the properties divided by the density.

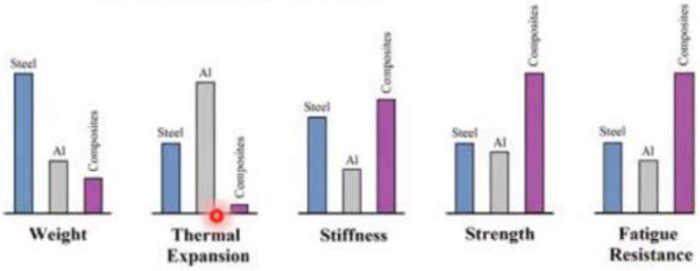




Advantages

Usually, for materials such as metals, you must design only the structure, in the case o the composite you have to design the material. Composites are engineered materials; we can engineer them specifically to meet our needs on a case to case basis. In general, following properties can be improved by using composite materials.

- Strength
- Modulus
- Weight
- Vibration damping
- Thermal stability
- Acoustical insulation
- Fatigue
- Aesthetics
- Resistance to wear
- Resistance to corrosion



Limitation

Like any material they have some limitation

- Anisotropy, this makes them more difficult to understand, analyse and engineer
- Non homogenous, their material properties vary from point to point making difficult to analyse
- Costly
- Residual thermal stresses, during the manufacturing process the coefficient of thermal expansion of the matrix and the fibres creates residual stresses which need to be accounted for
- Moisture effects, the matrix should insulate the fibres from the humid environment

Fibres

Fibres have

- High length to diameter ratio
- Its diameter approximates its crystal size, approximate 10 microns. This size its important to reduce the fatigue limit because, in fact for fatigue the smaller the size the better the properties.

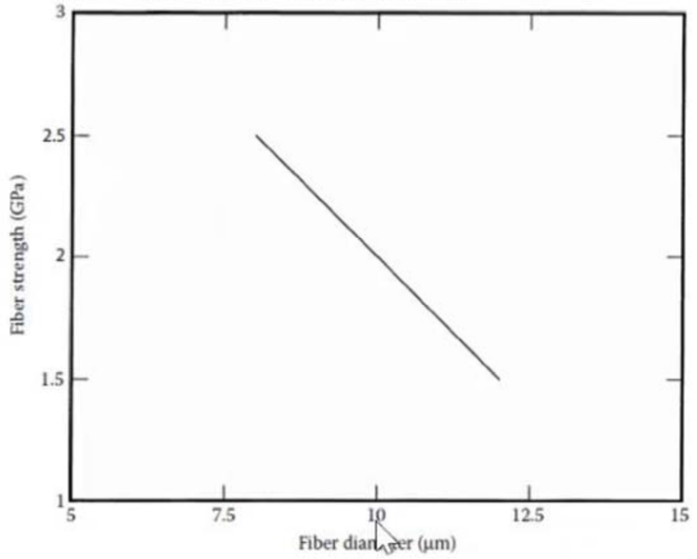
Modern composites exploit the fact that small scale samples of most of the material are much stronger than bulk materials. Thus, these fibres are 200 to 500 stronger than bulk glass.

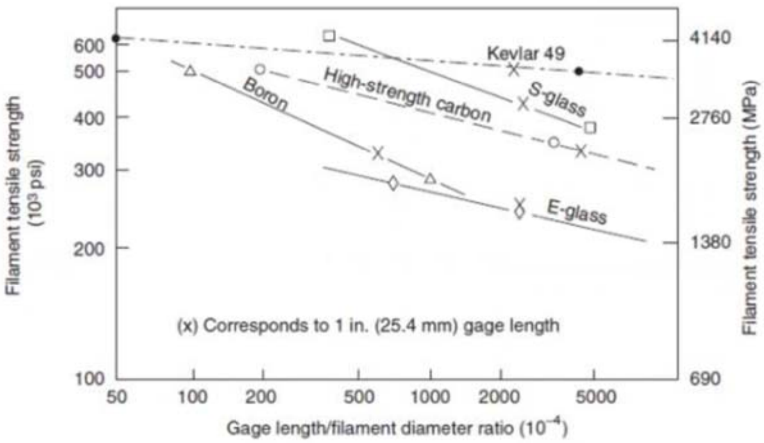
Several types of fibres are available commercially. Some of the more commonly used fibres are made from materials such as carbon, glass, Kevlar, and other metals.

Glass is the most popular fibre in composite since it is relatively inexpensive. It comes to two principal varieties, E glass, and S glass, the latter one is stronger than the former.

Fibres are significally stronger than bulk materials because

- They have the perfect structure, i.e. Their crystal is aligned along the fibre axis
- There are fewer internal defects orientation, and hence there are lesser number of dislocations. This is the cause of the size effects.





At larger scales, the degree of structural perfection within a material sample is far less that what is present at small (micro and nano) scales. For this reason, fibres of several engineering materials are far stronger that their equivalent bulk materials samples.

Table 2.1: Properties of Some Common Engineering Materials in Bulk and Fiber Forms

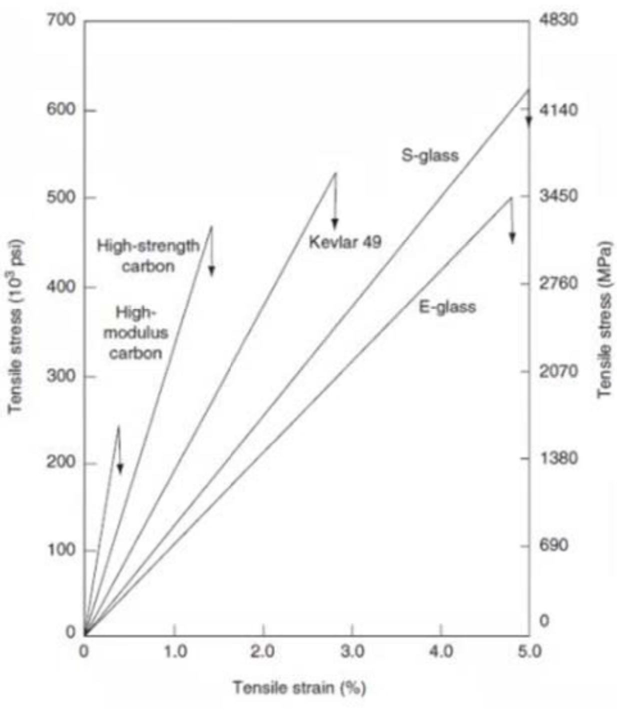
Fiber	Specific Gravity	Young's Modulus (GPa)	Bulk Tensile Strength (MPa)	Fiber Tensile Strength (MPa)
Aluminium	2.7	78	140-620	620
Titanium alloy/fiber	4.5	115	1040	1900
Steel	7.8	210	340-212	4100
E-Glass	2.54	72	70-210	3500
S-Glass	2.48	86	70-210	4600
Carbon	1.41	190	very low	2100-2500

This table shows the different strength for a variety of material in case of the bulk and the fibre form. The specific gravity is the ratio between the density of the metal and the density of water.

Properties of Selected Commercial Reinforcing Fibers

Fiber	Typical Diameter (μm)[a]	Density (g/cm^3)	Tensile Modulus GPa (Msi)	Tensile Strength GPa (ksi)	Strain-to-Failure (%)	Coefficient of Thermal Expansion (10^{-6}/°C)[b]	Poisson's Ratio
Glass							
E-glass	10 (round)	2.54	72.4 (10.5)	3.45 (500)	4.8	5	0.2
S-glass	10 (round)	2.49	86.9 (12.6)	4.30 (625)	5.0	2.9	0.22
PAN carbon							
T-300[c]	7 (round)	1.76	231 (33.5)	3.65 (530)	1.4	−0.6 (longitudinal) 7–12 (radial)	0.2
AS-1[d]	8 (round)	1.80	228 (33)	3.10 (450)	1.32		
AS-4[d]	7 (round)	1.80	248 (36)	4.07 (590)	1.65		
T-40[c]	5.1 (round)	1.81	290 (42)	5.65 (820)	1.8	−0.75 (longitudinal)	
IM-7[d]	5 (round)	1.78	301 (43.6)	5.31 (770)	1.81		
HMS-4[d]	8 (round)	1.80	345 (50)	2.48 (360)	0.7		
GY-70[e]	8.4 (bilobal)	1.96	483 (70)	1.52 (220)	0.38		
Pitch carbon							
P-55[c]	10	2.0	380 (55)	1.90 (275)	0.5	−1.3 (longitudinal)	
P-100[c]	10	2.15	758 (110)	2.41 (350)	0.32	−1.45 (longitudinal)	
Aramid							
Kevlar 49[f]	11.9 (round)	1.45	131 (19)	3.62 (525)	2.8	−2 (longitudinal) 59 (radial)	0.35

We can see that these materials are all brittle because the stain to ratio is below 5%



Material	Tensile modulus (E) (GN/m^2)	Tensile strength (σ_u) (GN/m^2)	Density (ρ) (g/cm^3)	Specific modulus (E/ρ)	Specific strength (σ_u/ρ)
Fibers					
E-Glass	72.4	3.5[a]	2.54	28.5	1.38
S-Glass	85.5	4.6[a]	2.48	34.5	1.85
Graphite (high modulus)	390.0	2.1	1.90	205.0	1.1
Graphite (high tensile strength)	240.0	2.5	1.90	126.0	1.3
Boron	385.0	2.8	2.63	146.0	1.1
Silica	72.4	5.8	2.19	33.0	2.65
Tungsten	414.0	4.2	19.30	21.0	0.22
Beryllium	240.0	1.3	1.83	131.0	0.71
Kevlar-49 (aramid polymer)	130.0	2.8	1.50	87.0	1.87
Conventional materials					
Steel	210.0	0.34–2.1	7.8	26.9	0.043–0.27
Aluminum alloys	70.0	0.14–0.62	2.7	25.9	0.052–0.23
Glass	70.0	0.7–2.1	2.5	28.0	0.28–0.84
Tungsten	350.0	1.1–4.1	19.30	18.1	0.057–0.21
Beryllium	300.0	0.7	1.83	164.0	0.38

Glass fibres

They are the most used and they come in two forms

- Continuous fibres
- Discontinuous or chopped fibres

Chemically, glass is silicon dioxide (SiO_2), they are used for structural application and can be either E glass or S glass, the firs one is much more common, and the name comes because they originate from the electrical applications.

Principal advantages

- Low cost
- High strength

Limitations

- Poor abrasion resistance causing reduced usable strength
- Poor adhesion to specific polymer matrix materials
- Adhesion in humid environments

The production of the material stats from the raw material, that then are put in a furnace at about 1500°C then the raw material is melt and then it passes through bushings forming fibres that are then woven around bundles. Generally, they are sold in packs bundles of 204 filaments