What are composites?

A short guide to fibre reinforced polymer composites, why they are useful and how they are made

Composites UK Trade Association

NATIONAL COMPOSITES CENTRE

COMPOSITES LEADERSHIP FORUM

Who are we?

Composites UK is the trade association for the UK composites industry. It acts to encourage continuous growth and development of the industry, promoting good practice. Its role is to bring companies throughout the supply chain together, creating partnerships, as well as being a unified voice to drive the industry forward.

compositesuk.co.uk

The **National Composites Centre** (NCC) is a research and development centre and is part of the High Value Manufacturing Catapult. The NCC mission is to accelerate the growth of UK industrial output by enabling design and manufacturing enterprises to deliver winning solutions in the application of composites.

nccuk.com

The **Composites Leadership Forum** is working to influence the government and other bodies (including industry, research centres, academia, skills providers) to bring together support for composites and ensure growth and industrial success for the UK. Fully supported by UK government, the CLF is chaired by industry with members drawn from industry sector groups, government, funding bodies and delivery partners.

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What is a composite?

A composite material is composed of at least two materials, which combine to give properties superior to those of the individual constituents.

This guide refers to fibre reinforced polymer (FRP) composites, usually with carbon, glass, aramid, polymer or natural fibres embedded in a polymer matrix. Other matrix materials can be used and composites may also contain fillers or nano-materials such as graphene.

The many component materials and different processes that can be used make composites extremely versatile and efficient. They typically result in lighter, stronger, more durable solutions compared to traditional materials.

Growth in the composites industry

The composites industry is an exciting industry to work in because new materials, processes and applications are being developed all the time – like using hybrid virgin and recycled fibres, faster and more automated manufacturing. The global composites materials market is growing at about 5% per year, with carbon fibre demand growing at 12% per year. With around 1500 British companies involved, the UK composites product market was estimated at £2.3bn in 2015, and could grow to £12bn by 2030[i].

Buildings and rides in the new Ferrari Land theme park near Barcelona use FRP composites cladding and roofing. The FRP parts were moulded using Scott Bader's ATH filled Crestapol® 1212 resin to meet stringent Euroclass fire performance ratings with excellent mechanical performance. Courtesy of Scott Bader

Why use composites?

Weight reduction

The primary reason composites are chosen is improved specific strength / stiffness (strength / stiffness specific per unit weight).

This helps to reduce fuel use, or increase acceleration or range in transport.

It allows for easier, faster installation or faster movement of robot arms and reduces supporting structures or foundations.

It improves topside stability in vessels and offshore structures and buoyancy for deep sea applications.

A Ferrari

Durability and maintenance

Composites don't rust, which is crucial, especially in marine and chemical environments. The need for maintenance and painting is reduced or eliminated.

Composite bearings for marine engines and bridges need no lubrication and don't corrode.

Combine the excellent fatigue resistance, and composites can increase product lifespan by several times in many applications.


A FRP walkway on an oil rig after 35 years of being in-situ. Fire resistant and durable, made with phenolic resin. Courtesy of Pipex px

Added functionality

Composites are thermal insulators which is good for fire and blast protection or cryogenic applications.

Electrical insulation is useful for railway lineside structures and radar transparency. A conductive mesh or coating can be integrated if needed, e.g. to reflect radar or divert lightning.

Sensors, electronics and cabling can be embedded.

Copper mesh or foil is integrated into the CFRP wing structure to protect from lightning

Design freedom

Composites design allows for freedom of architectural form.

Many parts can be consolidated into one, and stiffeners, inserts, etc. can be integrated in-mould.

Composites can be tailored to suit the application by choosing the constituent materials and embedding extra functionality.


Chanel Pavilion designed by Zaha Hadid comprising of 400 complex curved FRP façade panels. Courtesy of Arup

"Some things, such as the longest wind turbine blades, the deepest oil risers and the fastest racing cars simply can't be made without composites."

A short history

We have been using nature's extraordinary FRP composites (such as wood) for many thousands of years. Robert Kemp's patent filed in 1916, covered "light, strong and durable" materials for flying machines made from fibrous materials with binders such as Bakelite. Composites as we know them now began in the 1930s when Owens Corning started to produce glass fibres ('fiberglas') and DuPont made a resin to combine with the fibres to make a composite. Through the 1940s and '50s applications developed for structural aircraft parts, boat hulls and fishing rods[ii].

Trabant P50, Dresden 1961. Photo by Richard Peter, Deutsche Fotothek

In 1941 Henry Ford unveiled his plastic car, with panels reportedly made from soybean and possibly hemp fibres and phenolic resin. It was very resilient and a third lighter than its steel equivalent[iii] . A 12ft dinghy produced in 1951 by W&J Tod at Weymouth was probably the first production boat in Europe, using an early Crystic® polyester resin from Scott Bader[iv]. From 1955 body panels for the East German Trabant were made from compression moulded Duroplast, a composite of cotton fibres and phenol resins, all from waste materials.

An early 1950's Tod's dinghy. Courtesy of National Maritime Museum Cornwall

Carbon fibres were developed concurrently in the USA, UK (at Farnborough) and Japan in the early 1960s. Boeing and Airbus both introduced structural composites in commercial aircraft in the early 1970s. As the global polymer industry matured, it surpassed steel in terms of world production volumes in the 1970s. FRP composites have grown alongside this and continue to grow and find new applications.

Materials

The constituent materials, along with the processes by which they are combined, determine the properties of a finished composite part. The most commonly used raw materials are described here.

Fibres

E-glass is the most widely used reinforcing fibre. Silica sand, limestone and other minerals are melted in a furnace and allowed to fall through tiny holes in a platinum plate to create fibres around 5-24µm diameter. As they emerge they are 'sized' (coated to enable handling and bonding to the matrix), bundled together to form a 'roving', and wound directly onto a bobbin. Other types of reinforcing glass exist for higher strength or chemical resistance.

Carbon fibre fabric manufacture. Courtesy of Sigmatex

Carbon fibre is made from a precursor fibre, usually polyacrylonitrile (PAN). This is pyrolysed and converted at high temperature into a graphite (carbon) fibre about 6-7µm diameter. Carbon fibres make the stiffest and strongest composites.

Glass fibre fabric manufacture at Scott and Fyfe

Aramid (aromatic polyamide) fibres such as Kevlar® and Twaron® are noted for their excellent impact resistance, as well as other properties, and are widely used in armour applications. There are other high performance polymer fibres such as UHMWPE (ultra high molecular weight polyethylene) and HMPP (high modulus polypropylene).

Natural fibres such as flax and hemp are often used in automotive interiors and have good damping properties, which can work well hybridised with carbon. Basalt fibres are increasingly used, especially where alkali resistance is important.

Materials continued...

Resins

The resins used in composites are polymers – made of long, chain-like molecules. These may be thermoplastic or thermoset.

Composite Integration Ltd supplies resin injection equipment and processing technology for wind turbine blades. Courtesy of Composite Integration

Thermoplastics melt when heated and solidify when cooled. Commonly used thermoplastics include PP, PET, nylon, or, for high performance applications, PEI or PEEK.

Thermosets are cured by a chemical reaction when resin and hardener or catalyst are mixed, causing cross-links between the polymer chains. They will not melt, though will eventually break down when heated. Thermosets have better mechanical properties and chemical resistance than all but the most expensive thermoplastics.

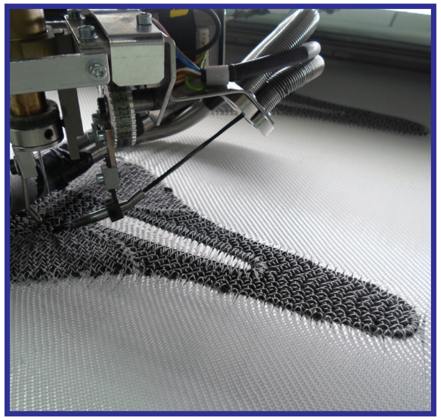
The most commonly used resin in glass fibre composites (GFRP) is unsaturated polyester. Vinyl esters are tougher and more water resistant than polyesters. Epoxy resins outperform most other resins and are usually used with carbon fibre. Phenolic resins have lower mechanical properties but very good fire resistance. Several other resin systems also exist.

Fillers and additives

Mineral fillers such as calcium carbonate are often included to reduce cost, as less resin is needed, while improving other properties. Other additives can be included, e.g. fire retardants, UV absorbers or toughening agents.

Intermediate materials

Fibres can be incorporated directly in some processes, but more often are converted into fabrics which may be uni-/ bi-/ multi-axial, woven, knitted, braided, needle-punched or simply chopped and bound into a random-oriented fabric. Textile engineering is an important aspect of optimising composite manufacture, and 3D preforms are increasingly being used, to align fibres exactly where they will provide the best properties.



Shape Machining manufacture 2D and 3D preforms in carbon fibre, such as this bike seat, using an embroidery technique. Courtesy of Shape Machining

Some fabrics, especially carbon fibre, are pre-impregnated with resin to form a 'prepreg', which usually needs to be kept in a freezer to stop the resin from going off until ready for use.

Bulk moulding compound (BMC) is a mixture of short chopped fibres, resin and filler, used in injection and compression moulding. It is also called dough moulding compound (DMC). Sheet moulding compound (SMC) is made by chopping longer (25mm+) fibres onto a layer of resin.

Reinforcing and thermoplastic fibres can be commingled to make a fabric which can be referred to as a thermoplastic prepreg. When heated, the thermoplastic fibres melt to form a matrix. Also, short fibres can be 'compounded' with thermoplastic resin for injection moulding.

Core materials

Using a sandwich of strong skins with a lighter core material is a great way to increase stiffness and reduce weight. Commonly used core materials may be polymer foams such as polyurethane, PVC or acrylic, or honeycomb structures made from aluminium, paper, Nomex® - (a Kevlar®-based paper) or other polymers. Balsa wood is an excellent natural core material with good fire resistance.

Manufacturing processes

There are many ways to process FRP composites and the method of processing needs to be considered in the early stages to decide what is best for each application.

The properties of the finished part are affected not just by the properties of the component materials, but also by the way the fibres are incorporated. Better fibre alignment and higher pressure in processing will improve fibre volume fraction, leading to better mechanical properties.

The cost of materials, mould tooling and equipment, the required finished properties and the number of parts to be produced will all be factors in deciding the process. The main processes used are described below.

Wet hand lay-up

Wet hand lay-up. Courtesy of MPM Ltd

This is a skilled manual process which requires low capital investment and is widely used for low-volume products, such as boats and bespoke products.

The reinforcement (as a woven or chopped strand fabric) is carefully laid into a mould and the matrix (resin) is applied and spread with a roller or brush. This is then left to cure at ambient temperature for several hours or overnight.

To get a good surface finish, a gelcoat can be added to the mould before the reinforcement is placed into it. The top surface is the side which is face down in the mould.

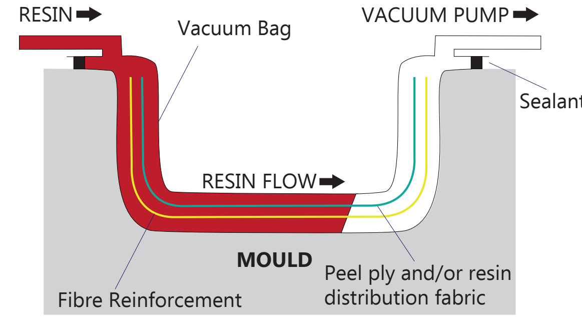
Wet spray up

Resin is fed through a tube and mixed with catalyst in a hand-held spray gun. The fibre (fed from a bobbin) is chopped into the resin stream as it is sprayed onto the mould. This is then left to cure at ambient temperature.

This is a quick and simple method, but leads to a low fibre volume fraction with randomly oriented fibres. Applications include custom parts in low to medium volumes, such as baths, swimming pools, storage tanks.

Vacuum infusion

Dry fabric plies (layered pieces) are laid up into the mould and covered with a film, or vacuum bag, sealed at the edges. The fabric is compacted under vacuum pressure as resin is drawn through from a reservoir. A flow layer may be needed between the fabric and the bag, especially for less permeable carbon fibre fabrics. This is good for large parts such as boat hulls, wind turbine blades or bridge structures.



Resin transfer moulding (RTM)

Dry fabric is laid into a two (or more) part mould which is then closed in a heated press. Resin is injected under pressure (e.g. 10 to 20 bar) until the fabric is impregnated and the tool is heated to cure the resin. The flow may be assisted by a vacuum (then referred to as vacuum assisted – VARTM).

Increasing the pressure reduces the cycle time, and the term high pressure RTM (HP-RTM) is used where the pressure is up to 150 bar in the mixing head and from 30 to 120 bar inside the mould, depending on part size and geometry. This process requires matched metal tooling, and is well-suited for mass production of 100 to 10,000 units/year.

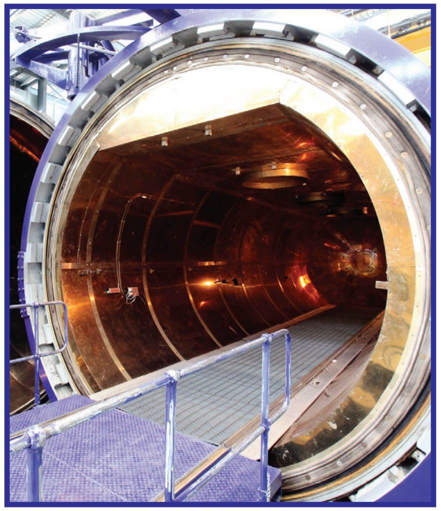
RTM light

A variant of vacuum infusion and RTM which combines the benefits of low cost tooling and equipment, with the simple impregnation process by resin pumping of RTM. The upper part of the mould is lightweight and can be flexible, in some cases using a silicone ‘bag’, made by spraying a silicone compound on a pattern. Aimed at low production rate parts.

Manufacturing processes continued...

Prepreg

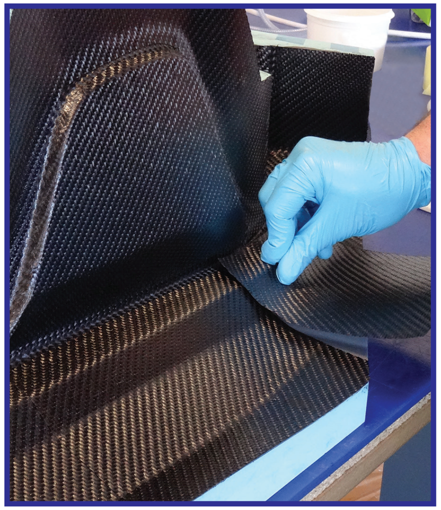
Prepreg fabrics (pre-impregnated with resin) are cut into plies (layered pieces) which are laid up, usually by hand, and smoothed onto the mould tool surface. This is the most popular process for high performance carbon fibre applications in aerospace and motorsport. Some manufacturers are now using automated tape-laying or automated tow placement rather than hand laid prepreg.



An autoclave at the National Composites Centre. Courtesy of the National Composites Centre

The part can be cured in several ways:

- **Autoclave:** The laid-up part is vacuum bagged and consolidated under vacuum, then cured in an autoclave (pressurised oven) at around 120-180°C and 2-6 bar.
- **Oven:** Vacuum bagged parts may be cured in an oven, with just the vacuum pressure applied. Low temperature prepregs are available, formulated to cure at 60-100°C at vacuum pressure. This is good for large parts where a big enough autoclave is not cost-effective.
- **Hot press:** Oven and autoclave processing typically takes several hours. For a shorter cycle time, the prepreg plies may be laid up into matched metal tooling and cured in a press under high pressure, with rapid heat transfer. The part can then be cured and demoulded in just a few minutes, but the tooling is expensive. It may be post-cured in an oven.

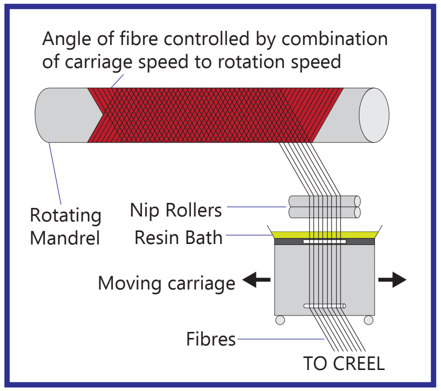


Carbon fibre headrest. Courtesy of Formaplex

Filament winding

Fibre tows are drawn through a liquid resin bath and wound onto a rotating cylindrical mandrel in a variety of orientations. This is often used to make pipes and tanks.

Multi-axis filament winding can be used to create pressure vessels or other shapes by winding the tow around a mandrel with shaped ends. The mandrel may then remain as an inner lining.



Moulding compounds

Moulding compounds have excellent electrical and fire protecting characteristics and 'Class A' surface finish from mould. In-mould flow means that fixtures can be incorporated in the part, reducing assembly costs.

Bulk moulding compound can be processed by injecting into a mould at high pressure or by compression moulding. Applications include automotive components, electrical equipment, household appliances.

SMC Lotus Engine cover. Courtesy of Creative Composites

Sheet moulding compound is compression moulded, and can be used in conjunction with woven / unidirectional fabrics or prepregs. Applications include light and tough vehicle body panels, electrical cabinets, shower trays.

Manufacturing processes continued...

Continuous processes

For a constant cross section product, several continuous processes are used:

Dawlish Station footbridge uses a combination of pultrusions and resin infusion to replace a listed iron bridge designed by Brunel. Courtesy of Tony Gee and Partners

- **Pultrusion:** Multiple rovings and/or fabric are pulled from reels through a resin bath into a heated die where the resin hardens and the shape is formed. The profile is pulled through the machine and cut to required lengths by an automated saw. Typical products are structural sections, cable trays, strips, bars or tubes.
- **Pullwinding:** As pultrusion, but a roving is wound onto the cured profile as it emerges from the die. This prevents the profile from splitting and increases flexural strength.
- **Continuous sheet:** Rooflights and flat sheet products can be made by spraying resin onto a moving carrier film and chopping fibres onto the resin. As this moves down into an oven, it may be shaped by passing over a profiled former. It is then trimmed to length.
- **Continuous filament winding:** As filament winding, but continuous for making long pipes.

Thermoplastics

Thermoplastic composites are usually produced by commingling polymer fibres with reinforcing fibres and heating in a mould so the polymer melts to form the matrix. In a hybrid process known as overmoulding, a short-fibre filled thermoplastic compound is injected onto a thermoplastic prepreg in a single mould. This can eliminate the need to add fixings, etc afterwards.

There are some thermoplastics that can be processed like thermosets, because they react and polymerise in the mould, but they can still be re-melted afterwards.

Design, data and automation

Design

Analysis and design of composite structures is complex because they are anisotropic and can involve many different constituent materials. Different processes and materials mean that ‘design for manufacturing’ is integral in developing a composite product. Various software packages provide early stage comparisons of composites with other materials, taking into account manufacturing processes and providing cost estimates.

Extensive databases of material properties exist and several composite design tools have been developed which are compatible with leading commercial 3D CAD systems. These now extend beyond structural / finite element analysis to integrate with manufacturing processes, surface engineering, and produce detailed drawings of how plies are cut and laid up, inserts are incorporated, etc.

Digital manufacturing

‘Nesting’ software optimises the layout of pieces to be cut from a roll of fabric, while still respecting fibre alignment, which significantly reduces waste. Tools now exist to show the operative exactly where to lay up the plies using optical imaging combined with virtual reality or laser projection. In some cases, automatic ‘pick and place’ systems are used. Tracking software can give vital information for each constituent of a part and each step of the process.

Kit cutting on a 12 metre ply cutter. Courtesy of A C Marine & Composites

There are now 3D printing processes which incorporate fibres, and hybrid parts can be made with a continuous fibre composite combined with 3D printed or injection moulded elements.

Skilled operatives are still very important, but automation is developing to improve consistency, quality and speed in manufacture.

What about fire?

FRP composites are very good thermal insulators, and panels to protect steel structures from jet fire on oil platforms were developed after the Piper Alpha disaster in the 1990s. There are several ways to protect FRP composites from fire, such as:

3 MW façade fire test on a large composite surface. Courtesy of RISE Safety/Fire Research

- Adding a fire retardant in the resin. The most used are halogen or phosphorus compounds, or ATH (aluminium tri-hydroxide) fillers
- Using a char-forming resin such as phenolic or furan
- Coating with an intumescent (swells to form an insulating layer when heated), ablative or protective coating (e.g. ceramic), or a layer of insulation

The polymers used as FRP matrices are combustible, but the commonly used thermoset matrices do not melt and typically burn less easily than thermoplastic materials. All composites will weaken and lose strength above their heat deflection temperature (HDT). Metals lose strength as temperature rises, too. HDT for a standard boatbuilding resin may be 80˚C, but some high performance resins are over 200˚C.

Can composites be recycled?

The stiffness, strength and durability that make composites environmentally excellent in use, also make them a challenge to recycle. However, there are several recycling solutions now.

Recycling carbon fibres at ELG Carbon Fibre

CFRP scrap goes through a pyrolysis process which decomposes the resin, leaving clean carbon fibres. These short fibres can be used in injection moulding, or made into fabrics, either commingled with thermoplastic or ready to be infused with resin to make new parts. There is still very little end of life CFRP, but manufacturing waste is being recycled in this way now.

Wind turbine blade section ready for shredding and disposal in a cement kiln. Courtesy of Agecko

Glass fibres are lower in value, so a different approach is taken. In some cases, ground GFRP is used in-house in new products. GFRP scrap can be co-incinerated in cement kilns, where the polymer is burnt for energy, and the glass (aluminosilicate) and any calcium carbonate filler is recycled into cement clinker. Increasingly, GFRP waste is being sent either to energy from waste or to cement kilns instead of landfill.

Natural fibre composites can be ground and used as filler, but as they are first-generation bio-derived, it makes sense to reclaim the embodied energy by combustion.

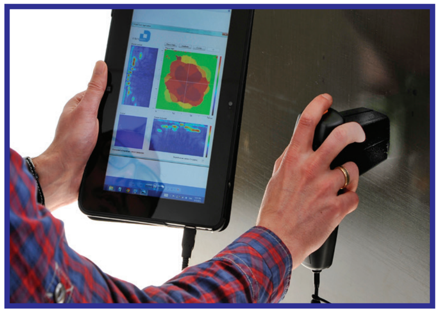
Thermoplastic composites can be shredded and compounded for re-use in injection moulding, though volumes are still small so this has yet to develop commercially.

Do we know how to repair composites?

We've had composites boats on the water for 70 years and commercial aircraft for 40 years, so we have learnt to repair them effectively. Composites are often used to repair steel pipes, concrete bridges and vehicles, as well. Repairs can even be carried out on wind turbine blades in situ, 100m above the ocean.

Repair of a wind turbine. Courtesy of Renewable Advice

As you would expect, successful repairs depend on good surface preparation, well designed repair procedures and the use of the right materials. Major repair of structural parts needs careful engineering design.



The DolphiCam ultrasound camera is a fast & cost effective method for NDT / inspection of CFRP. Seen here scanning impact damage. Courtesy of JR Technology Ltd

As composites don't easily dent like metals, it's not always easy to see if there is underlying damage after an impact. Various non-destructive testing and evaluation (NDT / NDE) methods have been developed, such as ultrasound, acoustic emission and laser shearography.

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Glossary

autoclave	Pressurised oven
catalyst	A substance that stimulates or speeds up a chemical reaction
class A finish	A surface finish having few surface defects and consistent colour and gloss, e.g. for a refrigerator door or car body panel
CFRP	Carbon fibre reinforced polymer
cure	Harden or set by a chemical process
GFRP	Glass fibre reinforced polymer
HDT	Heat deflection / distortion temperature - the temperature at which a polymer sample deforms under a specified load
mandrel	Cylinder around which material can be forged or shaped
matrix	Resin or other material used to bind together fibres or particles
nesting	Optimising how pieces are arranged to be cut from a roll of fabric
Nomex	A Kevlar-based paper often coated in phenolic resin for fire resistance, and used to make honeycomb core materials
PAN	Polyacrylonitrile, the most common material used as a precursor to make carbon fibre
PEEK	Polyether ether ketone, a high cost, high performance thermoplastic
PEI	Polyetherimide, high performance thermoplastic, comparable but inferior to PEEK
PET	Polyethylene terephthalate, a thermoplastic polyester best known for use in clothing and plastic bottles
ply	Layer which forms part of the laminated composite
PP	Polypropylene, a low cost, versatile thermoplastic used in carpets, plastic containers and many other applications
prepreg	Fabric which is pre-impregnated with resin
pyrolysis	Thermal decomposition by heating in the absence of oxygen
roving	A bundle of fibres
size	The coating on a fibre which improves bonding with the matrix and makes it easier to handle
thermoplastic	Polymer which melts when heated and solidifies when cooled
thermoset	Polymer which cures by cross-linking, so does not melt when heated
tow	A thick roving, defined by the number of filaments, e.g. 1k tow for high grade aerospace to 50k industrial grade tow