CompoTech Technology

CompoTech has perfected their unique axial fibre filament placement and winding technology over the last 20 years. This process results in true axial fibres laid with fibres of many other orientations designed to give the required properties according to the specification and optimised for effective and repeatable manufacture.

Every time a composite component is made the composite material and it’s material properties are also made. Composites can be very misleading. It is possible to have identical looking composite components made with identical fibres and matrix that have quite different physical properties. The visible fibre orientations may be the same, but internally the fibres could be laid in quite different directions. A repeatable manufacturing process and careful quality control is necessary so that each part is made consistently. At CompoTech, the manufacturing programme can only complete when all elements have been laid down in the order specified. At any stage a quality check can be implemented in order to know if the part is on course for correct manufacture.

The CompoTech Process

Introduction
CompoTech have developed their own processes, have designed and built all their unique machinery, have written all of the processing software and some of the design software.

An insight into the CompoTech process
Materials, Pin Winding, Possible Sections, Additive Manufacturing, Tooling and Production volumes

There are three areas of Composite development that are unique to CompoTech
Passive Composite Damping
– brings up to 20 times better damping than steel
Integrated Connections
– uses the fibre process to make effective connections to other components
3D Cellular Composite
– adds a Z axis fibre to thick composite.
Materials
The CompoTech process has been developed using all grades of Carbon Fibre, Aramid Fibre, and Glass Fibre.
The Ultra High Modulus Graphite Fibre (also known as Pitch Fibre) is a particular specialty and is proposed where it is beneficial.
CompoTech use only Epoxy resin for the composite matrix, but there are many types of epoxy resin which are appropriate.
Epoxy with dispersed Carbon Nanotubes has been proven to be especially effective with the CompoTech process.
The inclusion of damping material in the composite has been pioneered by CompoTech and the resultant big improvement in damping properties of machine components is particularly useful.

Pin Winding
CompoTech developed an automated “Pin” winding method of manufacturing composite tubes in 1994 and have been developing the process ever since.
The CompoTech process is now known as “Axial Fibre Placement”

By placing fibres along the axis of a tubular component it is possible to get a higher volume fraction, i.e. more fibres relative to the volume of material. More fibres in the composite gives:-

- 10% – 15% greater stiffness
- 50% better bending strength
Axial Fibre Placement enables more of the performing fibres to be placed to advantage in the section.
Some Simple Sections

A circular tube is the simplest product. With the CompoTech process fibres can be placed at any angle to the axis from 0˚ – 90˚. A simple tube with true 0˚ fibres will always be better in bending and stability than any other process.

All tubes with a variable thickness are made by adding axial fibres in an automated process. Adding axial fibres in the thicker places is always better for bending properties in that plane.

If sharp corners or dimensional accurate outside section shapes are required, then outside tooling is required. CompoTech have specialised in developing the process to make these sections accurately, repeatably and as economically as possible.

Of course CompoTech have many other sections and examples of other possibilities.

Additive Manufacturing

The CompoTech process is additive manufacturing. Most of the material added during manufacture is needed for the final part. Carbon Fibre is an expensive material and very little is wasted. It is possible to be cheaper than a metal equivalent part by saving on the cost of post processing and/or building in features in the tooling.

Tooling and production volumes

Tooling can range from the experimental one time use, to long lasting high volume production tooling. One tool may have multiple uses and for this reason all tooling is owned by CompoTech and used where appropriate. A tooling contribution charge is made when a new tool is needed, but it does not give ownership or control to the customer who made that contribution. Every new tool that is made is used in combination with other tools that are already existing, paid for by contribution from other customers.

Production volumes can vary from 1 – 1000s depending on the customer needs. Some experimental parts can be made from existing tooling or made from very cheap “one time” tools. Volume production, and consequently pricing, will depend on the required lead time and batch sizes. This will dictate the number of tools needed and how many parts are made on one tool.
Damped Composite
Composites are a lighter, stiffer and/or stronger material, but for many applications high damping is a desirable property. CompoTech have pioneered the inclusion of other materials which greatly increase the damping and dynamic stiffness of a composite component. CompoTech have a great deal of experience of designing damped composite to achieve the desired combination of properties.

3D Cellular Composite
3Dc is the term given by CompoTech to a series of processes that allow an effective three dimensional fibre composite. This composite consisting of a high axial fibre content in the X direction with fibres also in the Y and Z direction interconnecting them. The result is a cellular appearance in cross section. When it is necessary for a part to achieve very high axial stiffness in a thick section, 3D cellular composite was created to satisfy this requirement. The cellular structure enables a shear path across the section and very high fibre content in the cells. It also allows more interesting sections to be realised.

Integrated Connections
By using the fibre laying process and cleverly designed tooling it is sometimes possible to make connection devices in the part that save on post processing and other connecting devices. This requires our designers to need to know the complete proposed system in order to suggest this possible cost saving alternative.
Compare Material Properties

Introduction
Composites are Anisotropic, i.e. have differing properties in each direction. Metals are Isotropic and have the same properties in all directions. In addition the material characteristics of composites are made at the same time as the component is made.

Composite and Metals
A summary of fibre and matrix properties and how a “Steel Equivalent” composite might be.

Composite Characteristics
Typical composite properties and comparisons and other attributes.

Life Cycle Analysis
A brief look at the Eco-Credentials of Composites.

Composites and Metals

CompoTech specialise in Long High Performance Fibres in an Epoxy Matrix

<table>
<thead>
<tr>
<th>Fibre Type</th>
<th>Glass Fibre</th>
<th>Aramid Fibre</th>
<th>PAN Carbon Fibre, HS (High Strength)</th>
<th>Pitch Carbon Fibre</th>
<th>Epoxy Resin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Modulus $E_{L}$</td>
<td>74 GPa</td>
<td>130 GPa</td>
<td>230 GPa</td>
<td>640 GPa</td>
<td>3 GPa</td>
</tr>
<tr>
<td>Transverse Modulus $E_{T}$</td>
<td>74 GPa</td>
<td>5 GPa</td>
<td>15 GPa</td>
<td>6 GPa</td>
<td>3 GPa</td>
</tr>
<tr>
<td>Shear Modulus $G_{L,T}$</td>
<td>30 GPa</td>
<td>12 GPa</td>
<td>50 GPa</td>
<td>20 GPa</td>
<td>1.2 GPa</td>
</tr>
<tr>
<td>Ul. Tensile Strength $U_{L}$</td>
<td>2100 MPa</td>
<td>3000 MPa</td>
<td>5000 MPa</td>
<td>3800 MPa</td>
<td>T</td>
</tr>
<tr>
<td>Density</td>
<td>2500 Kg/m³</td>
<td>1500 Kg/m³</td>
<td>1600 Kg/m³</td>
<td>1900 Kg/m³</td>
<td>1100 Kg/m³</td>
</tr>
<tr>
<td>Relative Cost</td>
<td>1</td>
<td>8</td>
<td>6</td>
<td>18</td>
<td>2</td>
</tr>
</tbody>
</table>

These are the typical properties of various fibres used at CompoTech.

Glass fibre, Aramid or “Kevlar”, Polyacrylonitrile or PAN Carbon Fibre is the common Carbon Fibre and is used in Aerospace, Formula 1, Sporting Equipment and many other applications.

Pitch Carbon Fibre is also known as Graphite Fibre is made from a different precursor to PAN Carbon Fibre. Pitch Carbon Fibre is made from Coal-Tar Pitch and has a very much higher Modulus of Elasticity. Pitch Fibre is not as strong as Coal-Tar Pitch, but strong enough for high stiffness applications that it is good for.

*Pitch Fibre has a unique -negative coefficient of thermal expansion. This has its uses, see Zero Expansion Compensation*
There are various grades of all fibres, but even the highest modulus PAN Carbon Fibre Composite is never stiffer than steel. PAN Carbon Fibre Composite is much stronger than steel and a component can be made stiffer than steel by increasing the section modulus.

Composites made with Pitch Fibre can be as much as twice the stiffness of steel, whilst at the same time being about the same strength. Pitch fibres, however, are much harder to process because they break very easily.

CompoTech have developed reliable methods to process pitch fibre and are able to use the stiffness advantages, especially when making components for Machine Building.

Making a Pitch Fibre Composite to the same thickness as a steel plate it is possible to make a Composite nearly as stiff as steel… Ex 150 Gpa, Ey 150 Gpa, Gxy 50 Gpa.

If the thickness of the Steel Equivalent composite is increased by 30%, i.e. 6mm > 8mm, then the same stiffness is achieved, but the weight of the composite is still one quarter, 25% the weight of steel.
**Composite Characteristics**

**Mass**
Carbon composites are generally considered 4 times lighter than most steels.
Density of Steel is 7.8 kg/m³.
Density of Graphite Damping Composite is between 1.4 and 1.8 depending on composition.

**Damping**
Damping is up to 20 x better than steel when damping material is included in the Composite.
The inclusion of damping material will reduce the Composite E-Modulus, but the resulting Composite E-Modulus is still similar to standard steels.
The positioning of damping material in the component is an important element of the design process.

**Stiffness**
E-Modulus of a Graphite Layer in the direction of the fibre can be over 400 GPa using 760 GPa fibre.
a Quasi-Isotropic “Steel Equivalent” complete laminate will be an E-Modulus of 150 GPa, in both X & Y directions, hence the need to use 1.3 times the thickness to maintain the Equivalence of 210 GPa steel.
Optimising the stiffness in different directions or between bending and shear stiffness is a normal part of the design process which is not possible with steel.

**Strength**
The maximum strength of a “Steel Equivalent” composite is about the same as the yield point of standard steel at about 385 Mpa.
Many Machine Components need Stiffness or Damping rather than strength and the volumes of material necessary mean that the stress levels are consequently very low.

**Failure**
Composites do not have a yield point.
Composites could micro crack in the matrix at about 75% of ultimate load. This can be considered to be the composite equivalent of a yield point. However, unlike steel, the E-Modulus does not change and the stress strain curve is a straight line until failure. Composites fail in Compression or the compression side of bending at about half the tension failure stress levels.

**Fatigue**
The SN curve for Carbon Fibre Composites is very flat and significantly better than steel.

**Expansion**
PAN fibre has a positive coefficient of thermal expansion.
Graphite fibre has a negative coefficient of thermal expansion. When made into a composite it can be designed to have zero expansion in a specified direction, provided this does not conflict with other required properties.
Machining & Precision
In Composites it is not good to cut the fibres that are responsible for stiffness or strength. It is usual to add an extra layer of some material in order to create a machined surface. Carbon Composites machine well, but require special equipment for the safe disposal of dust or slurry. Accuracy of tooling dictates the accuracy of the part and this is very useful in obtaining accurate inside dimensions without machining. This can be a significant saving.

Toughness and Hardness
Carbon Graphite Composite does not have the toughness or hardness of steel. If there is a danger of damaging contact it is necessary to design some protection. Most machines already have external covers, so this is not usually an issue. For constant contact pressure it is possible to use a local coating to improve surface hardness.

Stability and Drift
Experimental measurements show that for precise positioning of a beam the CompoTech Composite is better than Prepreg Composite. The Prepreg beam would drift over micro-time and loses its positional stability. The reasons are that residual stresses are built into the prepreg beam during curing. The CompoTech production process does not have this problem and the CompoTech beams pass the criteria for stability.

Environmental
Corrosion
Epoxy Composites do not corrode.

Fluids
Epoxy resins are impervious to fluids, and a good composite has very low voids. However, if the composite is machined the surface of both the resin, any filler and the fibres may be cut. Anywhere that is machined needs to be re-coated to ensure a good seal.

Temperature
The Epoxy Resin Matrix is chosen partly for its temperature performance. Anywhere in the range -40°C to +200°C is normal. Higher temperatures may be possible.

Ultra Violet Light
UV is a problem for Epoxy Resins and there are many additives to reduce this degradation. However, this is only a surface problem and can be overcome with the correct choice of coating should there be any danger of UV.

Health & Safety
Once a Composite is manufactured, the only health hazard is dust from the machining, grinding or sanding of it. This is overcome by the use of fluids or strong air suction to remove any particles.

Recycling
Unwanted composite is chopped and the matrix burned off to recover the energy trapped in the chemistry. The short fibres are used for reinforcement in injection moulding or concrete. Other possible recycling processes will convert the material back to basic elements.
Life Cycle Analysis
Life Cycle Analysis [LCA] is the assessment of energy and other environmental impact and is specific to a product or component. Broadly speaking, the more often it moves, moves fast or accelerates & decelerates, the more competitive a carbon fibre component will be in an LCA comparison with other materials. This generally means that the LCA needs to be a Whole Life LCA and not a Factory Gate LCA in order to be competitive. A good example is the passenger jet. it can be shown to have 20% An LCA for a passenger jet will show a 20% saving when made with a great percentage of composites over the traditional all metal aircraft.
Composites for Machines

Introduction
Machines are dynamic structures with vibration from moving parts, milling teeth and motors. The resulting harmonics of the tool are the limiting factor in the performance and productivity of most machines.

Theory
Mass, Damping and Stiffness of the elements of a machine dictate its performance. See how composites can be better at all three.

Design Principles
These are a few considerations highlighted to help when looking at the design of a part from first principles in Carbon.

Cost Benefits
Carbon fibre is an expensive material, but there are many situations where it is far more cost effective to use.

The Theory
There are many advantages of using composite materials for machine components that are in motion. Less weight and higher stiffness means a higher natural frequency. More damping means less vibration and more accuracy. Less weight means less energy to accelerate & decelerate and all attributes together resulting in a higher output.

Natural Frequency is a function of Material Density and modulus. This is the equation:-

\[ m \cdot \frac{d^2 \Delta}{dt^2} + c \cdot \frac{d \Delta}{dt} + k \cdot \Delta = 0 \]

Vibrations and their decay are dependant on the Mass, Stiffness and Damping of the components of the machine as shown by the formula that governs force equilibrium in free vibration contains those three Material Properties. The other elements of the equation are Acceleration and Velocity, which combine into Frequency, and Displacement which is Amplitude.

CompoTech Carbon Graphite Composite Technology has significant beneficial effects on all three material properties.

- ¼ of the Mass of Steel
- 2 x the E-Modulus of Steel
- 20 x the Damping of steel
- …And the potential of Zero thermal Expansion
The Result
Alexander H. Slocum, Precision Machine Design 1994, shows the effect of improving the material properties one at a time…

The early tests at CompoTech were of a spindle tube of damped composite comparing with a steel spindle tube of the same dimensions.

This test shows the effectiveness of damped composite and the importance of improving all parts in a system.
A comparison of Grey Cast Iron with several CompoTech Carbon Graphite Damping Composites. 3 Trials of beams with the same outer sectional dimensions and varying proportions of Composite Modulus and Damping properties were all shown to have lower Amplitudes at higher Natural Frequency. Grey Cast Iron compared with Carbon Graphite Composite with differing combinations of E-modulus and Damping

- Good Modulus + lots of Damping
- High Modulus + Damping
- Very High Modulus + a little Damping

The results show quite clearly that the negative deflection G(f) at the harmonic frequency for the Composite Beams are significantly less than for Grey Cast Iron.

More metal can be cut in one pass by Increasing the Limit Chip and creating a larger area of Stable Machining in the Stability Lobe Diagram.

The Limit Chip formula and the results above indicate that the reduced negative vibration will promote a larger Chip size using Carbon Graphite Damping for the Beams of a Machine. In practise it is the interaction of every part of the machine which determines the Stable Area for Machining. In order to maximise the potential offered by Carbon Graphite Damping materials for the machine structure it will be particularly important to pay attention to the interface between the Composite and other parts of the machinery. Of particular importance is the bearing connection between sliding beams and other parts of the machine structure. It is important to look beyond the standard solution and consider all properties of the materials at this interface.
Design Principles
Composites is an Additive Process and many features can be formed when manufacturing a part. Smooth flowing Natural Shapes are more conducive to structural integrity in Composites. Fibres prefer to flow around corners and do not like sharp corners. Avoid square edge holes. Limit stepped shapes, indents, channels, inspection windows. For optimum cost and weight / stiffness ratio Composite Design is generally bigger than steel.

Optimised Composite Components may be a little larger than the steel version.
Damping will be better.
Weight will be less.
Less energy required.
Smaller motors, bearings, rails and similar components

Symmetry is important when taking differential expansion into account.

Thermal Behaviour
With a composite solution for a machine beam it is possible to achieve a better thermal stability, but the thermal deformation is much more complex than with a traditional isotropic material. A machine beam made from steel, cast iron, or aluminium will expand equally in all directions. Composites are not Isotropic and have both structural and thermal properties depending on the direction of the fibres in each layer and on each face of a component. Even if the cross section of a beam is symmetric, its thermal behaviour will be uneven. Adding only thin plates of steel to the composite will have a significant influence on the thermal deformations.
In 3 dimensions all the thermal deformation activity has to be balanced out at the ends of a beam and this will cause a local curling effect at the end of a section. Thermal behaviour in composite materials needs to be fully understood and modelled using Finite Element techniques in order to predict the precision of the component both during manufacture and in everyday operation of the machine. Even though the thermal deformations of composites are much more complex to understand and predict, the final result is less expansion than the isotropic metal equivalents.

Whole Complex System Thinking
The Spindle Motor Example

Thermal expansion of the various elements of the Spindle Motor will have an effect on machining accuracy. It follows, then, that for optimum accuracy tool-tip thermal displacement (Δ) should be minimized.

Carbon Graphite Composite offers the opportunity for negative thermal expansion alongside good strength and stiffness properties. Therefore the calculation needs to be done to balance the thermal expansion of shaft and tubus, and possibly holder and tool shank, in order to achieve zero Δ.

If we are to balance one thermal expansion load against another, then the load has to go through the bearings. This reaction will need to be within the capability of the bearings. The loads created by thermal expansion that are balanced by loads in another part will be dependent on the effective E-Modulus and the thermal expansion coefficient.
Benefit Estimation

Energy / Cost Comparison

The cost of Carbon Fibre is often raised as a reason for it not to be considered. This is a very false assumption. Carbon Fibre is expensive and consequently can only be justified by the financial benefits it can bring.

This has been done in many cases. Consider the simple example here. A beam designed in different materials to have the same stiffness to do the same task. The material price of Carbon Fibre seems unbelievably expensive, but by the time a beam of the same stiffness is built it is less than 4 x steel.

Start to move the beam and the price of motors, bearings and all systems could be hugely less and likewise the running cost. Add up the cost over a few years and the price of Carbon Fibre is easily justified.

This does not take into account the added benefit of better damping and so higher quality.

This is a simple spreadsheet and can be downloaded here...

Quality benefits are difficult to predict. Quality and higher production rates due to better damping are harder to predict, but are definitely achievable. Until there is a significant body of data, experimental methods will be the best way forward.