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REVIEW OF MANUFACTURING METHODS FOR STRUCTURAL PARTS FROM SHORT-FIBER POLYMERIC COMPOSITES AND METHODS FOR IMPROVING THEIR MECHANICAL PROPERTIES

REŠERŠE METOD PRO VÝROBU KONSTRUKČNÍCH DÍLŮ Z POLYMERNÍCH KOMPOZITŮ S VYUŽITÍM KRÁTKÝCH VLÁKEN A ZPŮSOBŮ ZLEPŠENÍ JEJÍCH MECHANICKÝCH VLASTNOSTÍ

BACHELOR'S THESIS
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As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Bachelor's Thesis:

Review of manufacturing methods for structural parts from short–fiber polymeric composites and methods for improving their mechanical properties

Brief Description:

The short–fiber polymeric composites has their main advantage in that they are very processable and do not make difficulties connected with layup process. However, their main disadvantage is low strength and stiffness. Therefore, they are mainly used for parts, where strength and stiffness properties are not critical. The improvement of strength and stiffness of such materials can allow to simplify the production technologies at least for airspace secondary structures.

Bachelor's Thesis goals:

1. Review of the state–of–art of manufacturing methods and analysis of their advantages and disadvantages.
2. Analysis of the state–of–art of methods for improving the mechanical properties of short–fiber composites and proposal of new progressive methods.

Recommended bibliography:

DE, S. K., WHITE, J.R.: ed. Short Fibre-Polymer Composites. Sawston, Cambridge: Woodhead Publishing, 1996. ISBN 9781845698676.

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BAJPAI, P. K., SINGH, I.: ed. Reinforced Polymer Composites: Processing, Characterization and Post Life Cycle Assessment. Weinheim, Germany: Wiley‐VCH Verlag GmbH & Co., 2019. ISBN 9783527820979.

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ABSTRACT

Short fibre polymeric composites are easier to manufacture than long fibre composites but this comes at the cost of worse mechanical properties (i.e. tensile strength and modulus). There are many ways to manufacture short fibre polymer composites. Most methods don't require manual labour and the methods are the same or at least very similar to manufacturing polymers. This makes short fibre composites relatively cheap. The mechanical properties of short fibre composites can be improved by aligning the fibres. Throughout the last 60 years multiple methods for aligning the fibres in the matrix have been developed. Most of these proved not to be practical for commercial use, but some of the more recent methods have shown great results; special emphasis is put on those in the respective part of the thesis. Additional two methods for aligning fibres are proposed; one using electric current and the other one a combination of alternating and static magnetic fields.

KEYWORDS

Composite, short fibre, polymer, short fibre polymer composite, fibre alignment, production methods, mechanical properties

ABSTRAKT

Krátkovlákenné polymerní kompozity jsou jednodušší na výrobu než dlouhovlákenné kompozity, ale za cenu horších mechanických vlastností (t.j. pevnosti v tahu a modulu pružnosti). Existuje mnoho způsobů výroby krátkovlákenných polymerních kompozitů. Většina metod nevyžaduje lidskou práci a metody výroby kompozitů a polymerů jsou stejné, nebo alespoň velice podobné. To vede k tomu, že krátkovlákenné kompozity jsou poměrně levné. Mechanické vlastnosti krátkovlákenných kompozitů mohou být zlepšeny zarovnáním vláken v matrici. Během posledních 60 let byla vyvinuta celá řada metod zarovnávání vláken, ale většina z nich se ukázala jako nepoužitelná pro komerční využití. Některé novější metody ovšem dosáhly výborných výsledků, a těm je v práci věnováno více prostoru. V práci je i návrh dvou nových metod k zarovnávání vláken, první pomocí elektrického proudu a druhé pomocí kombinace statického a oscilujícího magnetického pole.

KLÍČOVÁ SLOVA

Kompozit, krátké vlákno, polymer, polymerní kompozit s krátkými vlákny, zarovnání vláken, výrobní metody, mechanické vlasnosti

ROZŠÍŘENÝ ABSTRAKT

Využití polymerních kompozitů v poslední době zaznamenalo velký rozvoj nejen v letectví, ale i v mnoha dalších průmyslových odvětvích, včetně dalších druhů dopravy. Nejžádanější kvalitativní vlastností polymerních kompozitů je jejich vysoká specifická pevnost, modul pružnosti a dobrá odolnost proti únavovému poškození. Různé druhy kompozitů se však výrazně liší svými mechanickými vlastnostmi, složitostí výroby a s tím souvisejícími výrobními náklady.

Tato práce je věnována krátkovlákenným polymerním kompozitům, které jsou ve srovnání s dlouhovlákennými polymerními kompozity jednodušší na výrobu, a tím i levnější, ovšem za cenu horších mechanických vlastností (t. j. pevnosti v tahu a modulu pružnosti). Cílem této práce je popsat a porovnat metody výroby krátkovlákenných polymerních kompozitů a analyzovat metody ke zlepšení mechanických vlastností kompozitů s krátkými vlákny. Komerční aplikace těchto metod by v důsledku mohla vést ke snížení cen kompozitních materiálů a jejich využití v oblastech, kde je vyžadována vysoká specifická pevnost a tuhost a kde se dosud používaly dražší polymerní kompozity s dlouhými vlákny nebo použití kompozitů nebylo dosud možné kvůli neúměrně vysokým nákladům na jejich pořízení.

Práce vychází z rešerše literatury s cílem vyhledat a porovnat různé metody výroby krátkovlákenných polymerních kompozitů a prostudovat dosavadní návrhy metod pro zlepšení mechanických vlastností krátkovlákenných polymerních kompozitů, a na tomto základě se pokusit o návrh vlastních metod zlepšování mechanických vlastností.

První kapitola této bakalářské práce se věnuje popisu kompozitních materiálů. Popisuje kompozity obecně, jejich typy a typické vlastnosti, popisuje jejich výhody a nevýhody a uvádí i další podrobnosti o polymerních kompozitech s krátkými vlákny. Pozornost je věnována také tomu, co ovlivňuje mechanické vlastnosti konečného produktu. Tato část rovněž pojednává o současných a možných budoucích aplikacích kompozitů se zvláštním důrazem na polymerní kompozity s krátkými vlákny.

Druhá část práce vychází z předchozí rešerše literatury a podrobně popisuje způsoby výroby součástí z polymerních kompozitů s krátkými vlákny a rozebírá výhody a nevýhody každé ze zmíněných metod. Na konci kapitoly je tabulka s porovnáním výrobních metod.

Třetí část práce pojednává o stávajících technikách zlepšování mechanických vlastností polymerních kompozitů s krátkými vlákny a podrobně popisuje jejich princip a výhody i nevýhody.

Poslední část předkládá návrh dvou nových metod, které by rovněž mohly vést ke zlepšení mechanických vlastností krátkovlákenných polymerních kompozitů, s jejich výhodami a nevýhodami.

Bylo zjištěno, že nejuniverzálnější běžně používanou metodou pro výrobu krátkovlákenných polymerních kompozitů je lisování, a to díky široké škále použitelných materiálů, popřípadě prepregů, které mohou mít i zarovnaná vlákna. Spray-up je naopak

mnohem levnější a jednodušší metoda, nabízející jedinečné možnosti, jako je výroba na místě použití výrobku. Její nevýhodou je však menší objemový podíl vláken, což omezuje maximální pevnost. Injekční vstřikování je rychlá a široce rozšířená metoda výroby polymerních součástí, a výrobní stroje vyžadují pouze drobné úpravy, aby mohly být použity pro výrobu kompozitů. Novou, rychle se rozvíjející metodou je aditivní výroba (3D tisk), která má velký potenciál, i když její použití pro výrobu kompozitů je teprve v počátcích.

Vývoj metod pro zlepšení vlastností kompozitů s krátkými vlákny v posledních třech desetiletích zaznamenal vzestup vzhledem k obnovenému zájmu o pevné, ale relativně levné kompozitní materiály. První metody, které byly vyvinuty, byly hydrodynamické metody a používaly viskózní kapaliny. Použití viskózních kapalin však komplikovalo a prodlužovalo výrobu. Později byly vyvinuty pneumatické metody, které byly sice rychlejší, ale přesnost zarovnání vláken byla ve srovnání s hydrodynamickými metodami velmi špatná. Objevily se i další progresivní přístupy, jako jsou metody založené na ultrazvuku nebo elektrickém či magnetickém poli. Jimi vyrobené materiály však mají nízký objemový podíl vláken a/nebo nedostatečnou kvalitu zorientování vláken. Byla také publikována metoda, která pomohla zarovnat vlákna během injekčního vstřikování, ale nikdy se komerčně neprosadila. Nová slibná metoda pro výrobu vysokopevnostních krátkovlákenných kompozitů se nazývá „HiPerDiF“. HiPerDiF je hydrodynamická metoda, ale na rozdíl od ostatních hydrodynamických metod používá vodu, která je méně viskózní než ostatní používané kapaliny, což výrazně zvyšuje produktivitu. Je navržena tak, aby umožňovala velkoobjemovou výrobu prepregů s mnohem lepšími mechanickými vlastnostmi ve srovnání se všemi ostatními metodami. Pro zarovnání vláken je vhodná i aditivní výroba, ale podobně jako běžný 3D tisk kompozitů se technologie stále vyvíjí a ještě není dostatečně vyspělá pro větší komerční použití.

V této práci byly navrženy dvě nové metody zlepšování mechanických vlastností. První metoda by používala elektricky vodivá vlákna a matrici a k zarovnání vláken by došlo interakcí magnetických polí generovaných proudem protékajícím vlákny. V současnosti však neexistují elektricky vodivé polymery, které by se běžně pro výrobu kompozitů používaly. Pokud by tato metoda fungovala tak, jak je zamýšleno, umožnila by, aby vlákna byla zarovnána kolem různých tvarů, a vlákna by proto lépe přenášela a absorbovala zatížení, a tak by zlepšila pevnostní vlastnosti kompozitní součásti ještě více než jednosměrné zarovnání vláken.

Druhá metoda je založená na hypotéze, že po vložení elektricky vodivých vláken do střídavého magnetického pole, by za jistých podmínek došlo k zarovnání vláken se směrem magnetického pole. Výhodou by bylo, že elektricky vodivá by musela být pouze vlákna.

Díky kombinaci nízké hmotnosti kompozitů, díky které jsou stroje využívající kompozity méně energeticky náročné a mají vyšší účinnost než stroje čistě kovové, a kvůli rostoucímu tlaku na udržitelnost a snižování produkce uhlíku lze očekávat, že se poptávka po levných vysokopevnostních kompozitech bude neustále zvyšovat. Proto má smysl se zabývat zlepšováním výroby kompozitů, zejména v oblastech, kde je velký potenciál ke zlepšení a minimální konkurence, a to jak z ekonomického, tak i enviromentálního hlediska.

BIBLIOGRAPHIC CITATION

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DECLARATION

I declare that this thesis on **Review of manufacturing methods for structural parts from short–fiber polymeric composites and methods for improving their mechanical properties** has been composed solely by myself with the use of literature and other sources listed in the references.

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Datum Jméno a příjmení

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TABLE OF CONTENTS

1. INTRODUCTION

The use of polymeric composites has lately seen a great increase not just in aviation but in a plethora of industries including other kinds of transportation. Their most desirable quality is typically their high specific strength and stiffness and their biggest downfall is high price to manufacture. There are many types of composites varying in their mechanical properties and manufacturing costs. In the first, general chapter I am going to concentrate on all kinds of composites, in the following chapters I will focus just on those with polymeric matrix and short fibres. This kind of polymeric composites is considerably cheaper and easier to manufacture than long-fibre polymeric composites but at the cost of mechanical properties. If these properties were to be improved, it would both simplify manufacturing and lower prices in places where polymeric composites are already in use. Perhaps more importantly it could open up a large number of such applications where use of composites had not been possible before either because of lacking strength or prohibitively high costs. Furthermore thanks to the combination of low weight of composites, which makes machines made of composite materials more efficient than machines from metals, and the growing pressure on environmentalism, sustainability and lower carbon emissions it can be expected that the demand for low-cost high-performance composites will be growing in the future. It makes therefore sense to research methods for improving the mechanical properties especially in areas with a great potential and minimal competition, both from an economic and an environmental standpoint.

This thesis consists of 3 major parts:

The first part of the thesis is about composites themselves. It describes composites in general, their types and typical properties, describes their advantages and disadvantages and, last but not least, gives more details on short-fibre polymeric composites. It also highlights what affects mechanical properties of the final product. This part also discusses current and possible future applications of composites with special emphasis on short fibre polymeric composites.

The second part then details the methods of manufacturing parts from short-fibre polymeric composites and discusses the advantages and disadvantages of each of the mentioned technologies.

The last part then discusses existing techniques for improving mechanical properties of short-fibre polymeric composites and in the end an additional method is proposed.

2. DESCRIPTION OF COMPOSITES

2.1. GENERAL INFORMATION AND COMPOSITION

Definition

Although in the past any product created from more than one material was considered to be a composite, nowadays the definition is narrower. Composites are considered to be created by combining two or more materials in a deliberate and distinct manner in order to enhance/optimize the properties of individual components. This can be achieved by using the desirable properties of each of the materials making up the composite or even obtaining new properties that neither of the components would exhibit on its own while mitigating some of the unfavourable properties of the components. These do not have to be just mechanical properties but also physical or chemical ones. [1,2]

In all composites the resulting material has properties superior to its components. Perhaps the most desirable result for aerospace engineers is that composite materials are stronger while being lighter and therefore have a much higher strength-to-weight ratio in comparison to conventional materials such as steel or aluminium. The resulting weight saving in aviation is on average between 15% and 25%. Another highly desirable quality in aviation is their great resistance to fatigue. Composites have however higher raw material price and they are much harder to repair then metals. [1,3]

History and applications

Although the use of man-made (engineered) composite materials is relatively new in comparison to traditional materials such as metals, rock, etc., there are natural composites that had been used long before the term composite was defined. Even the first powered flight was done with an airplane built from a composite – wood. Wood is a composite of celulose fibres dispersed in lignin matrix. Another example of a natural composite is bone or concrete. [1, 3]

In more recent history the use of composites has spread in areas where the need for a lightweight high-performance material and benefits of its use outweigh the increased costs of materials and manufacture. Although there are many products made from composites these days, there is one field that has benefited from their discovery more than others – transportation. Whether it is a boat, a car or an aircraft, the use of composites has increased exponentially since the first use of modern man-made composites. There are many more current applications such as wind turbine blades and sporting equipment to name a few. [3]

The history of the use of modern engineered composites dates back to 1964 when carbon fibres were discovered. However it wasn't until the late 60s when composites found their way into secondary structures (doors, primary and secondary flight control surfaces, etc.) of military aircraft. Another leap forward came with CFRP (carbon fibre reinforced polymers), which thanks to their good mechanical properties managed to displace some of the metal primary structures such as wings, fuselages, fins and tailplanes. Another use of composites in airplanes would be the now common use of carbon-carbon brakes whose first notable use was on Concorde in the late 60s or helicopter rotor blades from glass fibre composites. [3]

Modern general aviation aircraft are, however, the true testament to the popularity of composites in civil aviation. Most clean-sheet designed airplanes such as Diamond DA-62 or Cirrus SR (first flown in 1999 and currently the best-selling general aviation aircraft) are made almost entirely from composites. And the same tendency of increasing the percentage of composites in an airframe can be seen in commercial aviation as well. Composites have been used for certain parts of aircraft for a long time and new airplane types from this millenium, notably Airbus A350, A380, Boeing 787 or Bombardier CSeriers/Airbus A220, are more than 50 % by weight from composites, similar to general aviation aircraft. An illustration of the materials used on Airbus A350 can be seen in Figure 1. [3]

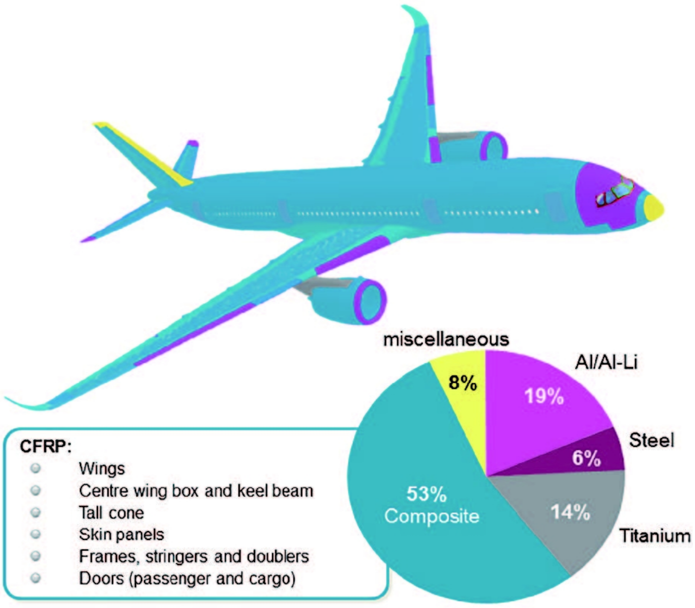


Figure 1: Materials used on Airbus A350 [4, pg. 1302]

2.2. COMPONENTS OF COMPOSITES, THEIR FUNCTION AND DIVISION

Composites are made by combining discontinuous reinforcements with a continuous matrix. Each of these components plays a very important and a very different role in the final composite material. There are several types of both matrixes and reinforcements, and their combination has a decisive role on the resulting characteristics (from manufacturing, mechanical and economic point of view). [3]

2.2.1. THE MATRIX

2.2.1.1. FUNCTION OF THE MATRIX

The matrix is the solid continuous phase that has several functions. Its main purpose is to bind the reinforcement (particles, fibres) together in a desired orientation while separating them. Without being properly bound, the composite wouldn't be able to hold its shape, would be too brittle and not be useful as a material for engineering uses. The matrix also transfers external stresses to the reinforcement. Furthermore, the matrix protects the reinforcement from mechanical damage and environment and it plays a key role in impact and abrasion resistance. Ductile matrixes give the composite its toughness while brittle ones rely on fibres to stop propagation of cracks. [2, 5]

2.2.1.2. TYPES OF MATRIX MATERIALS

Polymer matrix

Polymer matrixes are among the most used kinds thanks to the simplicity of their manufacture, low cost and desirable mechanical properties. They increase ductility but have low strength, therefore parts from polymer composites gain their strength from the reinforcement while the matrix improves toughness. It is therefore imperative that there is a strong bond between the polymer matrix and the reinforcement. Polymers have one major disadvantage – their low resistance to higher temperatures. The limiting temperature is the cured glass transition temperature (T_g) at which thermoplastics start becoming soft and semiflexible. For thermosets the limit is typically 30°C below T_g because thermosets start absorbing large amounts of moisture at increased temperatures (presence of moisture can be particularly problematic in changing temperatures due to thermal expansion of trapped moisture, which can cause cracks to develop). [2, 5]

There are two kinds of polymer materials used – thermosets and thermoplastics. Thermosets start as a low-viscosity resin that forms its well bonded 3D crosslinked structure during processing and they can no longer be formed or otherwise processed after curing. Thermoplastics on the other hand start as a high-viscosity resin and

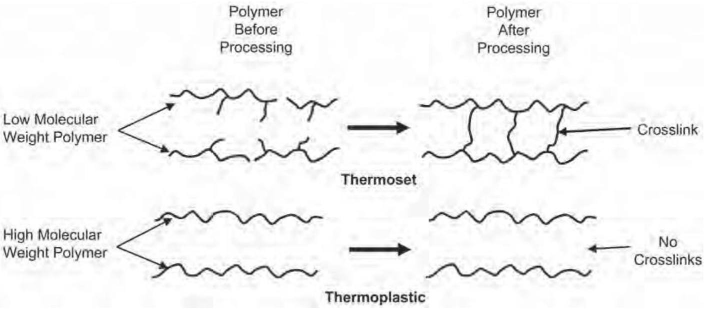


Figure 2: Comparison of thermoset and thermoplastic structure [5, pg. 63]

form a simpler 2D or 1D structure and do not chemically crosslink. Both structures can be seen in Figure 2. Thermosets can, however, stay in a partially cured condition (and therefore be formed) for a longer period of time. The processing times for thermosets are relatively long due to the chemical reaction that needs to take place during the curing process. [2, 5]

Thermosets

Thermosets are best suited for use in conjunction with fibre reinforcements. The most common types are epoxies, polyesters, vinyl esters, furan resins, phenolics and polyimides. One deciding factor on the exact thermoset kind to be used is the operating temperature. While polyimides can be used up to 315°C, epoxies can only be used to 130°C. Polyesters and vinyl esters are similar to epoxies in the temperature usability range, but they have worse mechanical properties and worse resistance to environment. Newer types such as cyanate esters offer better resistance to moisture absorption, which is a typical problem for thermosets. Some cyanate esters also have desirable electrical properties. Phenolics are, on the other hand, used in aircraft interiors thanks to their fire and smoke resistance which makes them ideal for such use; they are, however, brittle. Another subcategory are toughened thermosets. They can withstand high temperatures and can stabilize the reinforcing fibres in compression, but they have a tendency to delaminate even after low energy impacts. That combined with the fact that this damage can not be seen from the outside makes them potentially hazardous. Although these days there are toughened thermosets that have greatly improved this undesirable characteristic, they have slightly worse mechanical properties and they are inhomogenous and anisotropic. A comparison of the damage resistance of the 1st-generation and modern toughened composites is in figure 3. [2, 5]

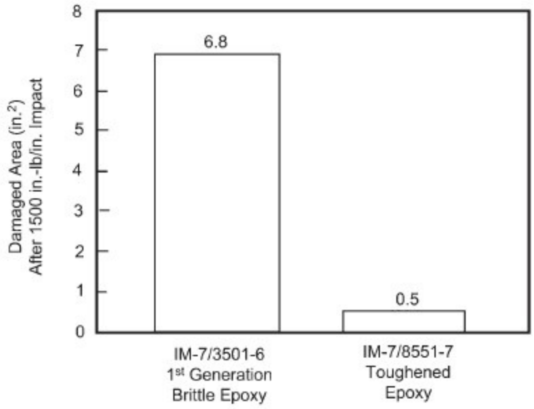


Figure 3: Damage done to 1st generation and modern toughened composite [5, pg. 77]

Thermoplastics

Thanks to their simpler structure, thermoplastics are more ductile than thermosets, and therefore offer better resistance to low velocity impacts and damage in general. They are much faster and easier to process than thermosets, they do not pose any risks to workers, as there are no chemical processes involved in the manufacturing process, and they are easy to store. They also absorb less moisture than thermosets. With increasing temperatures they become soft and melt. This allows them, however, to be formed multiple times. Softening at higher temperatures can be mitigated to a certain degree with the use of appropriate fillers. [2, 5]

There are several types of thermoplastics but the number is fairly limited compared to their boom in the 1980s. There are two groups – semicristalline and amorphous.

Polyetheretherketones (PEEK), polyetherketoneketones (PEKK), polyphenylene sulfides (PPS), and polypropylenes (PP) are semicristalline. PP is used exclusively with discontinuous glass fibres and is used extensively in the automotive industry. Other thermoplastics are normally used with continuous fibres. Highly aromatic thermoplastics offer good fire resistance. An example of an amorphous thermoplastics is polyetherimide (PEI). The difference between semicristalline and amorphous structure is shown in figure 4. [2, 5]

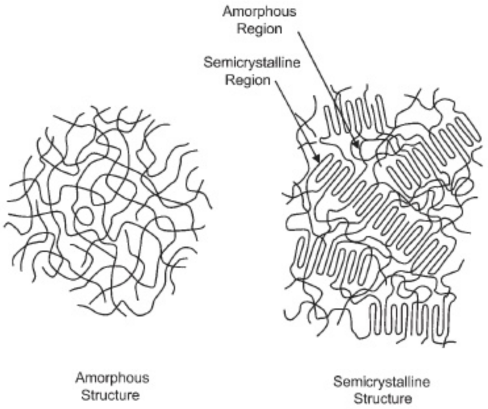


Figure 4: Amorphous and semicrystalline thermoplastic structures [5, pg. 84]

Metallic matrix

Metallic matrices are stronger, stiffer and tougher than their polymer counterparts and they have better thermal resistance. They are, however, more complex to manufacture and process and they are heavier. Most alloys could be used, but in practice only a select few light metals are regularly used – aluminium, magnesium and titanium. [2, 5]

Ceramic matrix

A ceramic matrix differs from the previously mentioned ones by being brittle on its own. It is therefore desirable for the bond between the matrix and the reinforcement to be weak since it is the matrix that makes the composite strong, and the reinforcement is what makes the composite ductile by stopping the propagation of cracks. Ceramics also make the composite resistant to high temperatures by having high melting point and being resistant to corrosion. This makes them suitable for uses where they face extreme temperatures and thermal shocks such as heat shields for space vehicles, brake discs, slide bearings or components in gas turbines. [2, 5]

Carbon matrix

Carbon matrices are made from graphite and they have vastly superior properties to other kinds of matrix. They are similar to ceramic matrices by being strong, resistant to high temperatures and being brittle. The most common kind is a carbon reinforced carbon composite (sometimes called carbon-carbon or just carbon composite). Their use is also similar to ceramic matrices – main uses are heat shields and brakes (most modern airliner brakes are from carbon composites). [2, 5]

2.2.2. THE REINFORCEMENT

2.2.2.1. FUNCTION OF THE REINFORCEMENT

Similar to the matrix, reinforcements are solid phase but unlike matrices are discontinuous. There are many types of reinforcements varying in material, size and shape. Reinforcements mainly influence the strength and the price, but they can also change the physical properties such as the thermal and electrical conductivity. The main function of the reinforcement is to add strength, which matrices typically lack. The reinforcements are also often brittle and therefore rely on the matrix to give the final composite ductility. Certain types of reinforcement can also be oriented in a certain way which can further improve the composite's final mechanical properties. [2,5]

2.2.2.2. COMMON TYPES OF REINFORCEMENT

Particles

Particles have no defined shape and they range from powders to very short fibres. They have several advantages one of which is their low price. Another advantage is that they can be packed very closely, which can make the composite conductive if a conductive reinforcement is used. They, however, provide minimal to no increase in strength and due to their irregular size and oftentimes sharp edges can actually weaken the composite and are therefore only used if special physical properties are needed or when there is a need for a lower price along with no requirement for greater strength. [2, 5]

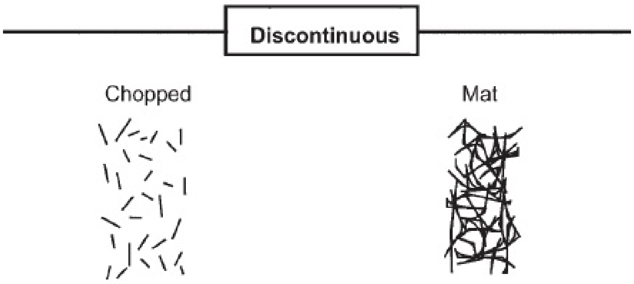


Figure 5: Types of short-fibre reinforcement [5, pg. 2]

Fibres

Fibres are reinforcements that are significantly longer in their longitudinal axis than in their other axes. The ratio between length and diameter is known as the aspect ratio and depending on the aspect ratio they are divided into short (discontinuous) and long (continuous) fibres. They usually have a circular or a nearly circular cross section. They are also strongly anisotropic since they are much stronger in their longitudinal axis than in the other ones. [2, 5]

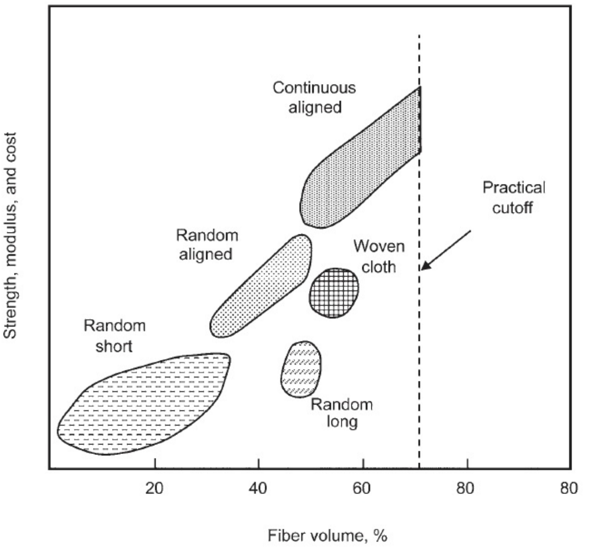
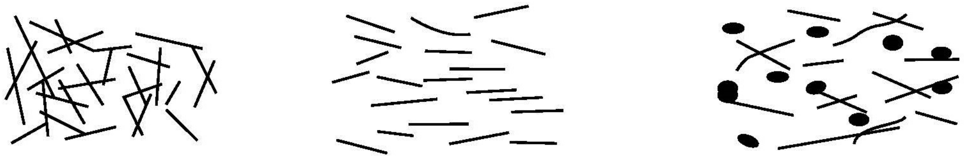
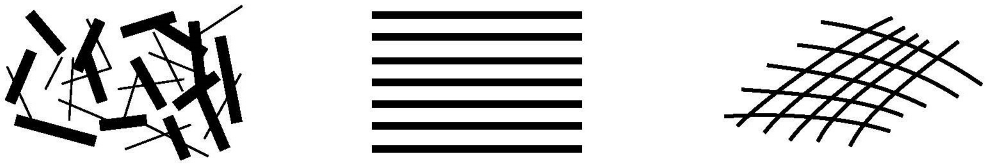


Figure 6: Properties of various types of fibres [5, pg. 3]

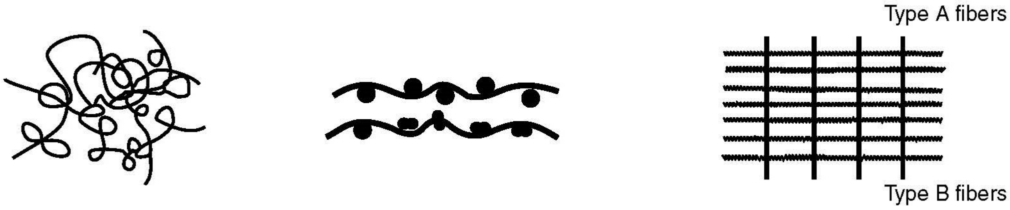
Discontinuous fibres are typically oriented randomly in the matrix, which



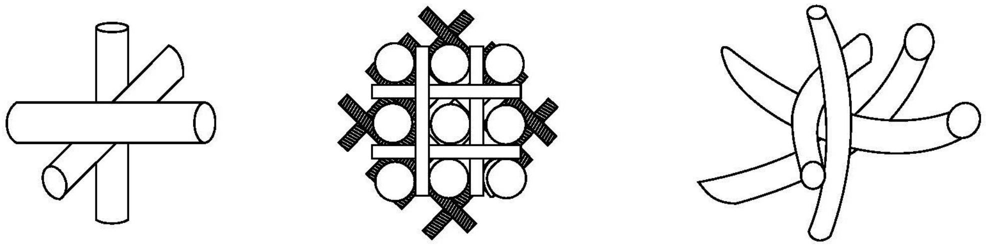
Chopped fibers (random) Oriented short fibers Fiber/Particulate hybrids



Short fiber hybrids Unidirectional continuous fibers Filament wound cylindrical



Long/Interpenetrating Woven fabrics Continuous/Hybrid



Orthogonal 3-D Multi-axial 3-D weave 3-D braid

Figure 7: Reinforcement types and combinations [2, pg. 7]

results in worse mechanical qualities in comparison to continuous fibres. Two common short fibre reinforcement types are in figure 5. Long fibres typically have a preferred orientation or can be woven into fabric-like structures and then layered into laminates. Short fibre composites have, however, one major advantage – their lower price. A comparison of the relation of the strength, modulus or the cost to the percentage of the fibres in a composite is in figure 6. Figure 7 shows further examples of reinforcement types and combinations of orientations and configurations. [2, 5]

Fibres are commonly made of glass, carbon or graphite, aramid, silicon carbide. Glass fibres have high tensile strength and good impact and chemical resistance. Carbon fibres are on top of that more resistant to fatigue and are the go-to material for high end applications. Aramid fibres are organic and are between glass and carbon fibres in terms of mechanical properties. [2, 5]

Whiskers

Whiskers are small pure monocrystallic structures shaped in a certain way. They are extremely strong but hard to distribute evenly through the matrix. [2, 5]

2.3. SHORT FIBRE POLYMER COMPOSITES

Definition

SPFC are made of a combination of short fibres and either a thermoset or a thermoplastic. For the most part all the principles already discussed apply to SFPC as well. [6]

Advantages of SFPC

Thanks to the cheap and simple manufacturing process of the short-fibre composites, they are nowadays used extensively in the automotive industry, for sporting goods and other durable consumer goods but also in the electrical industry. [6]

They offer superior mechanical properties in comparison to particle composites while maintaining a lower price than continuous fibre composites. They also offer better surface quality than continuous fibre composites. Furthermore they allow for manufacturing of complex shapes that could not be made with long fibre composites. [5]

Fibres in SFPC and their effect on mechanical properties

Fibres in SFPC improve the properties in which polymers are lacking, namely strength and elastic stiffness. Fibres do, however, also reduce toughness. The fibres typically have diametres of the order of 10 µm. The most common type of fibres are glass fibres (around 90% of SFPC are made with glass fibres). Other less common options include carbon or boron, silicon carbide, aramid and polyethylene fibres. All of these have better mechanical properties and do not self abrade like glass fibres, but they are more expensive. Hybrid composites using more than one kind of fibres are also used. [6]

In SFPC the fibres are stressed by the deformed matrix via the interfacial bonding strength. Therefore the final strength is highly dependent on the bonding strength and the strength of the fibres themselves. The fibres are usually coated with a coat protecting them from abrasion and a coat to enhance the interfacial adhesion. [6]

The fibres in SFPC need to be longer than the critical length, which is given as:

$$l_c = \frac{1}{2} \cdot \frac{\sigma_f}{\tau_i} \cdot d$$

where l_C is the critical length, σ_f is the tensile stress of the fibre, τ_i is the shear stress at the interface and d is the diameter of the fibre. This assures that the fibre would break because of tension and not because of fibre shearing from the matrix. The optimal length is, however, much longer. If the length was 5 times higher than the critical length and the fibres were aligned perfectly, the composite would have 90% of the strength of its long fibre counterpart. The exact strength ratios for different fibre lengths can be seen in figure 8. [5, 7]

It should also be noted that the tensile stress drops to zero at the ends of the fibre and it is the highest in the middle, while the shear stress is distributed the opposite way. The tensile stress around a fibre can be seen in figure 9. [5]

The angle of the fibres relative to the stress direction also drastically changes the tensile strength and modulus of the final part. A chart plotting the effect of the angle can be seen in figure 10. [5]

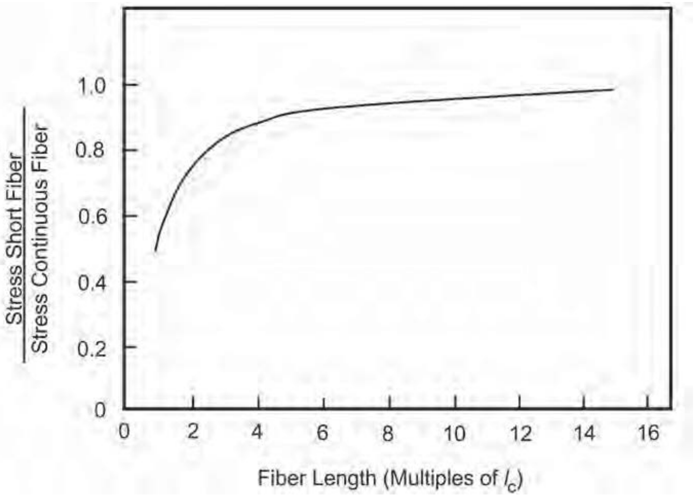


Figure 8: Effect of fibre length on tensile strength [5, pg. 287]

Manufacturing SFPC

The most common type of a manufacturing process is injection moulding. Injection moulding is a conventional method for polymers alone, unlike the manufacturing methods for continuous fibre composites, which require much more time and labour, making them unsuitable for mass use. There are, however, other manufacturing methods; and those will be discussed in detail in the next chapter. [6]

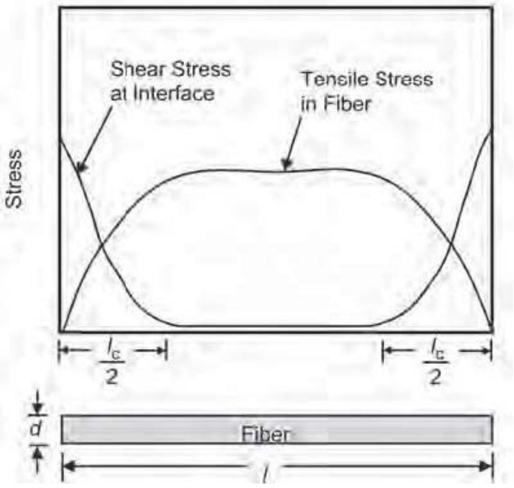


Figure 9: Stresses around a short fibre [5, pg. 286]

Summary of mechanical properties of SFPC

The mechanical properties of the SFPCs do not deviate from what was already described in previous chapters. They can be influenced by the properties of the materials used and by the morphology of reinforcement distribution – fibre length distribution, fibre volume fraction and fibre orientation, which can be controlled during the manufacturing process. The interfacial bonding strength between the matrix and the fibres also plays a very important role in SFPC. [6]

SFPC can also be infused with inorganic fillers such as short glass or short carbon fibres to increase SFPC's thermal conductivity, which is for example required in electronics. Some short fibres can also lower SFPC's thermal expandability, which tends to be quite high with polymers. [6]

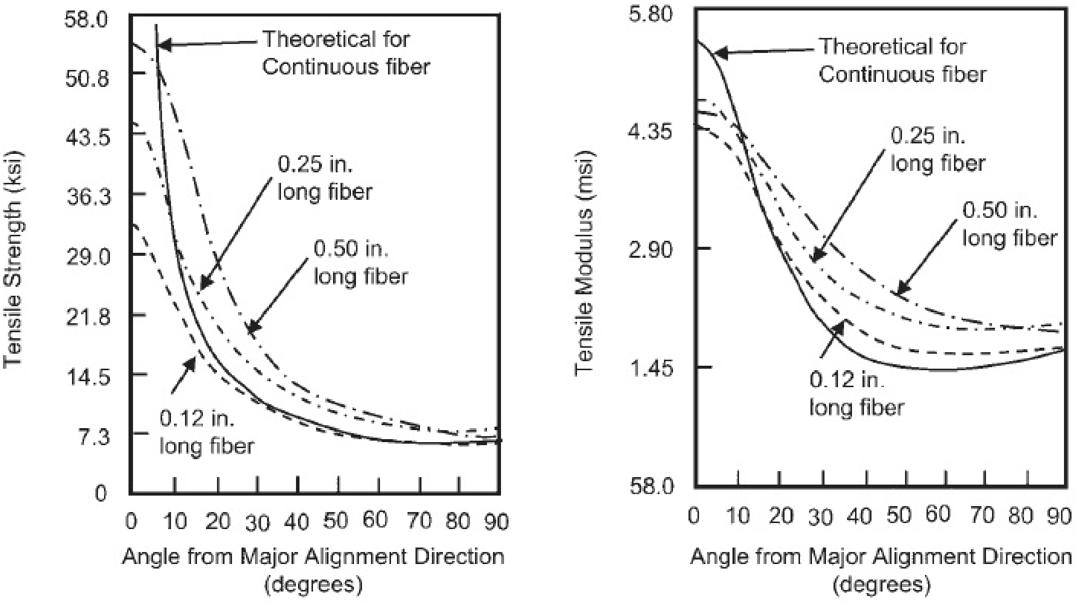


Figure 10: Strength and modulus as functions of load-fibre alignment [5, pg. 288]

2.4. ADDITIONAL PROPERTIES OF COMPOSITES AND OTHER DESIGN CONSIDERATIONS

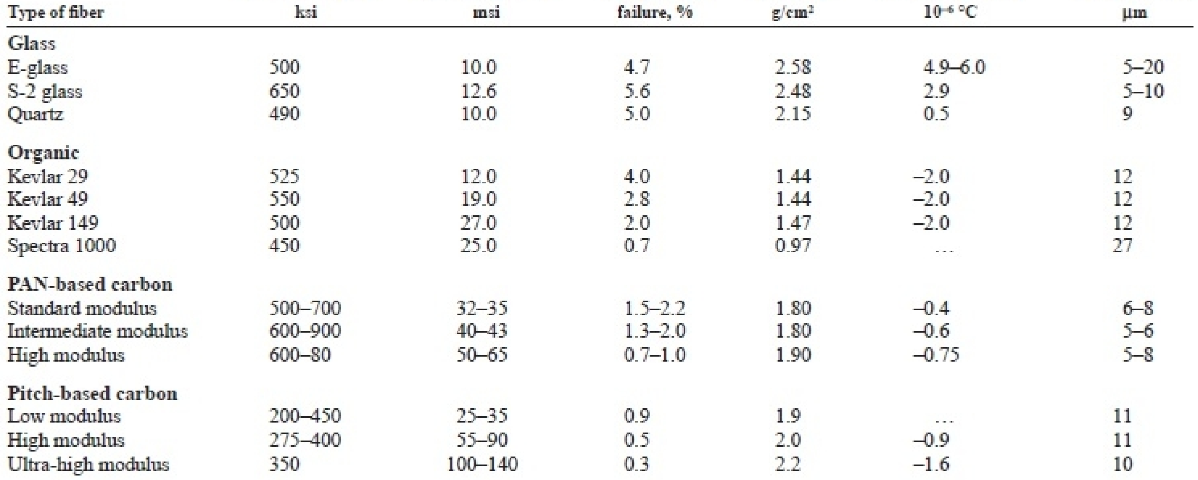
The mechanical properties of composites are highly dependent on both the combination of the matrix and the reinforcement but also on the type and quality of the manufacturing process. If for example the fibres failed to be properly separated by the matrix, cracks could pass through the composite without being stopped. [2, 5]

The mechanical properties are also heavily influenced by the amount of the reinforcing phase. Too little would mean that the material would not properly reinforce the matrix and hence would have little effect on increasing the strength (or ductility in the case of ceramic/carbon matrix). Too much reinforcement, however, is not desirable. The theoretical maximum of the reinforcing phase that can be in a composite is around 70 volume % as higher percentage would result in the matrix not binding the filler properly. [5]

Another component determining the quality of a fibre composite is the quality of the fibres themselves. Desirable fibres are those with few defects on their surface. This is typically easier to achieve with a thinner fibre, and therefore the thinner the fibre is, the better its relative strength due to less defects in its smaller volume. This is also the reason why fibres are typically much stronger than the bulk material they are made of. A comparison of a variety of commonly used fibre materials can be seen in table 1. One disadvantage of making the fibres thinner is the increased cost. [5]

A key characteristic determining the strength of a composite is the grip of the matrix on the fibres since the matrix needs to effectively transfer the load onto the fibres otherwise the composite would only be as strong as the matrix which is typically quite weak. [2, 5]

Table 1: Comparison of commonly used high strength fibres [5, pg. 32]



Type of fiber	Tensile strength, ksi	Tensile modulus, msi	Elongation at failure, %	Density, g/cm²	Coefficient of thermal expansion, 10⁻⁶ °C	Fiber diameter, μm
Glass						
E-glass	500	10.0	4.7	2.58	4.9–6.0	5–20
S-2 glass	650	12.6	5.6	2.48	2.9	5–10
Quartz	490	10.0	5.0	2.15	0.5	9
Organic						
Kevlar 29	525	12.0	4.0	1.44	–2.0	12
Kevlar 49	550	19.0	2.8	1.44	–2.0	12
Kevlar 149	500	27.0	2.0	1.47	–2.0	12
Spectra 1000	450	25.0	0.7	0.97	…	27
PAN-based carbon						
Standard modulus	500–700	32–35	1.5–2.2	1.80	–0.4	6–8
Intermediate modulus	600–900	40–43	1.3–2.0	1.80	–0.6	5–6
High modulus	600–80	50–65	0.7–1.0	1.90	–0.75	5–8
Pitch-based carbon						
Low modulus	200–450	25–35	0.9	1.9	…	11
High modulus	275–400	55–90	0.5	2.0	–0.9	11
Ultra-high modulus	350	100–140	0.3	2.2	–1.6	10

Another favourable characteristic of composites is their great resistance to fatigue.

A comparison with conventional materials can be seen in figures 11 and 12. This is the reason why cyclically stressed parts (such as helicopter rotor blades) are almost exclusively made of fibre composites. [5]

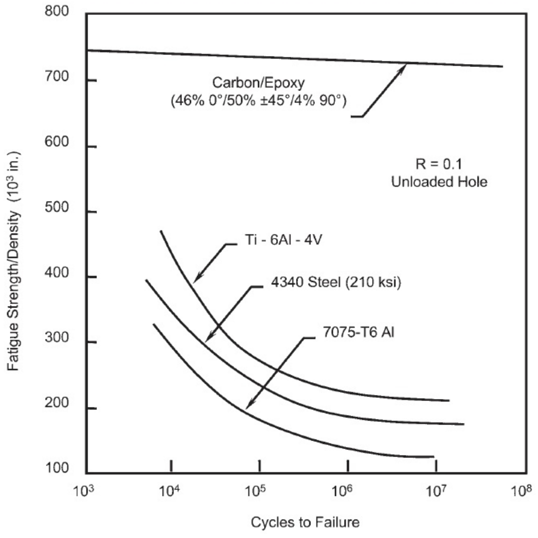


Figure 11: Fatigue properties of aerospace materials [5, pg. 16]

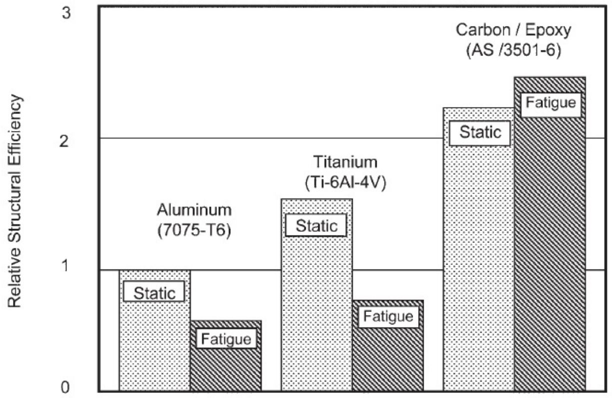


Figure 12: Relative structural efficiency of aerospace materials [5, pg. 15]

Another highly desirable quality is the corrosion resistance of composite materials. This makes them very popular in industries with highly corrosive environments, for example the chemical industry or marine applications, where they are often used in place of metallic materials or wood. [5]

Reduced assembly costs can also be a factor in choosing a composite structure. Composites can be shaped into a wide variety of shapes, thus reducing the total amount of parts, fasteners and labour required for the assembly. One major operational problem of composites (especially of those with a hardened thermoset matrix) is that they can be damaged easily and it is more difficult to detect and repair the damage than with metals. [5]

Operating temperatures are also a factor when it comes to mechanical properties. With increasing temperatures the matrix dominant properties typically decrease. Less apparent is the effect of lower temperatures, which affects the fibre-dominated properties. [5]

Another major way to influence the properties of fibre composites is the way the fibres are oriented. Composites with fibres that are aligned along one direction, preferably the one in which they are stressed, are much stronger than those with the fibres placed randomly. One side effect of orienting all fibres in one direction is the resulting anisotropy (or even orthotropy). Note that Young's modulus differs depending on the direction. This can be mitigated with use of laminates that are made from multiple layers facing different directions. [2, 5]

3. MANUFACTURING METHODS OF SFPC

There are many methods of manufacturing short fibre polymer composites, some of them similar or identical to the methods used in manufacturing and forming polymers. In the following I am going to describe and analyse the most common ones – injection moulding, spray-up and compression moulding and their respective subtypes or similar methods. Complete list and classification can be seen in figure 13.

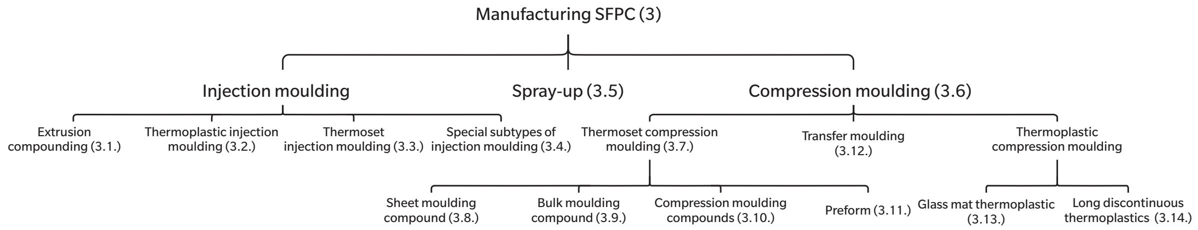


Figure 13: The classification of SFPC manufacturing methods

The processing should result in a good bond between the matrix and the reinforcing phase, proper orientation of the fibres, proper volume fraction of the reinforcement, uniform distribution of the reinforcement in the matrix, proper curing or solidification of the matrix, minimum of defects and voids and a good control over the shape of the final part. [6, 7]

A good bond is important for proper transfer of loads from the matrix to the fibres. If the fibres do not bind properly to the matrix, dry spots may occur, in which cracks can start. On the other hand, dry spots slightly increase the impact resistance. A good bond between a matrix and a fibre can only be achieved if they are compatible, which means that they need to wet properly (surface energy of the matrix has to be smaller than surface energy of the fibre). This ability can be improved by various surface treatments, which is a common practice with carbon fibres. Another important requirement for a good bond is that there is enough liquid matrix available at the surface of the fibre. [7]

Proper orientation is important since the strength and the stiffness are highly sensitive to even small deviations. Therefore it is desirable that fibres are aligned in one desired direction if they are going to be exposed to simple loading in one direction. In the case of loading from multiple directions, the opposite is true – it is desirable for the fibres to be oriented randomly. [6, 7]

Another key element is to limit the formation of defects and voids. Voids appear when there is not enough compaction between layers, or when the pressure of the matrix is too low. [6]

It is also important to consider that the part shrinks as the matrix cures or solidifies, which leads not only to a change of shape but also to residual stresses. [7]

3.1. EXTRUSION COMPOUNDING

General information

Extrusion compounding is the process that precedes injection moulding the goal of which is to create a homogenous dispersion of the fibres in the matrix. The polymer is mixed with the fibres and granulated for use in the injection moulding process. [6]

Description of the tools and the manufacturing process

Extrusion compounding happens in a machine with a screw in a barrel, which melts and mixes the compound. The polymer-fibre mixture is forced against heated walls, mixed and then in the end forced through a die, which shapes the composite into sheets, profiles, films, etc. It is then cooled with water and cut. The last step, if needed, is granulation in a granulator, which creates granules, which are going to be used in injection moulding. [6]

Advantages, disadvantages and other considerations

There are several advantages to extrusion compounding. The melting happens gradually, it is easy to control the temperature and it is easy to make large quantities of the composite. There are, however, disadvantages too. There is a limit to fibre volume which is around 40 to 45 %. Furthermore, the fibres get damaged and break during the process. This makes them shorter and consequently the final composite material weaker. There are several reasons why the fibres get damaged. Some fracture due to high stress concentration from abrasion, others break due to bending stresses appearing on overlapping fibres. Contact with the equipment can also damage the fibres and so can the viscous forces from the matrix. There are, however, ways to mitigate the degradation of the fibres. [6]

3.2. THERMOPLASTIC INJECTION MOULDING

General information

Injection moulding can facilitate large scale manufacturing and the products made using injection moulding require little to no further processing after they are removed from the mould. After the initial investment into the moulds it is very inexpensive and can produce very complex shapes. It is suitable for use with fibres that are 0,8 to 3 mm long. [5, 6]

Almost all thermoplastics can be used and so can some thermosets, and although everything in the following will be concerning injection moulding of thermoplastics most of it should also apply to injection moulding of thermosets, which has a dedicated chapter at later. [5]

Glass fibres are the most common reinforcement type but if better mechanical properties and/or electrical properties such as electromagnetic shielding, antistatic properties, etc. are desired, carbon fibres can be used. Colour pigments, fillers, mould release agents, lubricants and other additives such as fire retardants can also be added into the mixture. [5]

Description of the tools

The machine for injection moulding consists of 2 major parts – a clamping unit and an injection/plasticizing unit. The former consists of an opening and a closing mechanism and a clamping mechanism that has to withstand the increased pressure during the moulding. The injection unit can be either a screw or a plunger type, with the screw being the superior tool for mixing. [5]

There are several types of screws and every composite compound requires a different one since each composite requires a different pressure during the injection into the mould. The compression ratio of the screw is therefore one of the most important design characteristics of the screw. Most screws feature 3 sections or zones – feed section, transition/compression section and metering section (figure 14). The feed zone works similar to a conveyor belt and it moves the compound further down the barrel. In the transition zone the composite compound is melted and homogenized and fed to the 3rd zone. The metering zone works as a pump generating pressure and metering the amount and rate at which the molten composite exits into the mould. The exact type of screw depends mostly on the polymer used. Examples of 3 screw designs can be seen in figure 15. The screw in figure 15 (a) is intended for use with highly crystalline polymers that have a sharp melting point and therefore it has a short compression section. The screw in figure 15 (b) is for semicristalline thermoplastics and has a longer compression section and figure 15 (c) shows a screw for amorphous materials that do not have a true melting point and therefore the compression occurs along the entire length of the screw. [5, 6]

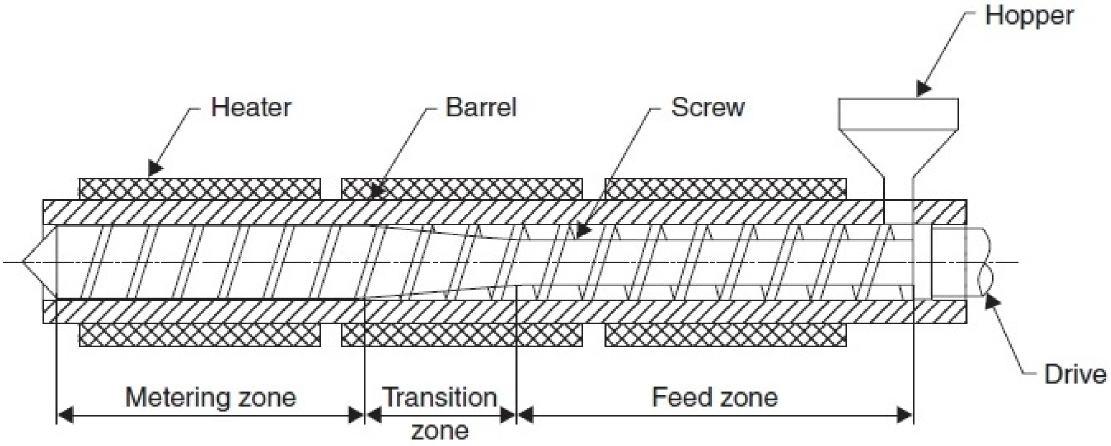


Figure 14: Typical screw shape and parts [6, pg. 16]

The mould is a cavity machined from metal (typically tool steels or aluminium with a coating), in which the final shape of the part is formed. There are several types of moulds. There are two-plate cold-runner moulds, in which the material is injected through a sprue, a runner system and gates, all of which have to then be manually removed. Another type is a three-plate cold-runner system. This type adds a plate which separates the sprue, gates and the runner system allowing for easy removal and recycling. The last commonly used type is a three-plate hot-runner system, where the compound is kept in molten state in the runner system, the sprue and gates, which allows for even easier separation and recycling.

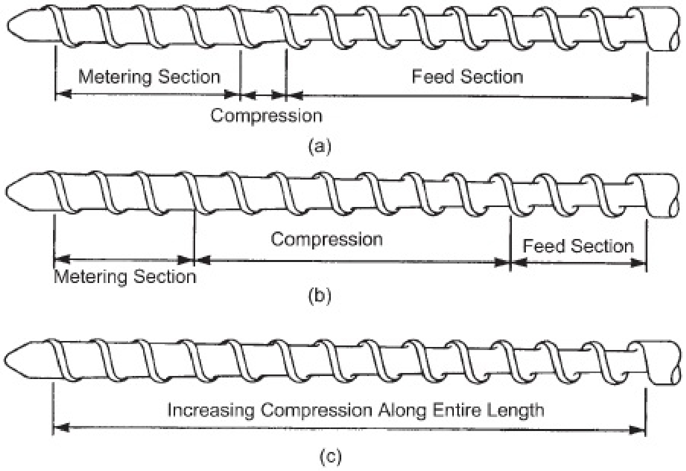


Figure 15: Injection moulding screw designs [5, pg. 302]

The sprues and runners also have to be designed to have smooth bends and be short to avoid drops in pressure. The design and placement of gates also needs to be considered as they control the flow rate into the mould, control the rate of solidification and lead to the formation of weld/knit lines, which form when 2 flow-lines come together. Most moulds use waterlines for cooling, which needs to be uniform to prevent residual thermal stresses and warping. The moulds also feature a vent to allow for the air in the mould to escape as it is filled with the molten compound. [5]

Description of the manufacturing process

Before the compound is injected into the mould it needs, to be dried (polymers absorb moisture that could lead to defects in the final part). Nonhygroscopic polymers such as polyethylene or polypropylene are moist only on the surface and only their surface is heated during the drying. Nylon and polycarbonate are, however, hygroscopic and require more time in a flow of dehumidified warm air. [5]

After the required amount of composite gets injected into the mould, the screw stops rotating and pushes forward like a ram. This forces additional compound into the mould, thus compensating for the shrinkage of the cooling-down part. Typical injection pressures range from 70 kPa to 100 MPa, and the minimum back-pressure on the screw should be between 170 and 350 kPa. [5]

After 20 to 120 seconds the part solidifies enough for the part to be removed from the mould. The solidification time is influenced by the mould shape and thickness, the amount of the reinforcing phase, etc. The cool-down time also dictates the cycle time of the moulding machine. [5]

Advantages, disadvantages and other considerations

One of the most important things to control during the injection is the temperature. Lower temperatures mean less cool-down time and higher volume of parts made, but at the cost of worse quality due to residual internal stresses and imperfect fibre orientation. [5]

During the injection into the mould, where high-speed flow through a narrow gate occurs, the fibres orient themselves parallel to the flow. Then, in the mould, the fibres in the boundary layer near the walls orient themselves parallel to the flow direction due to high friction between the flow and the walls. In the centre of the part, where there is less friction, the fibres orient themselves transversely to the flow. This leads to structures with surface layers having fibres oriented in the same direction while in the middle there are fibres oriented in different directions (as can be seen in figure 16). There may be cases, in which due to the nature and direction of the stresses on the part, this behaviour can be undesirable because of the resulting anisotropy. If this is the case, the temperature of the injected composite should be increased, the speed of injection be lowered and the gate can be made larger. [6, 7]

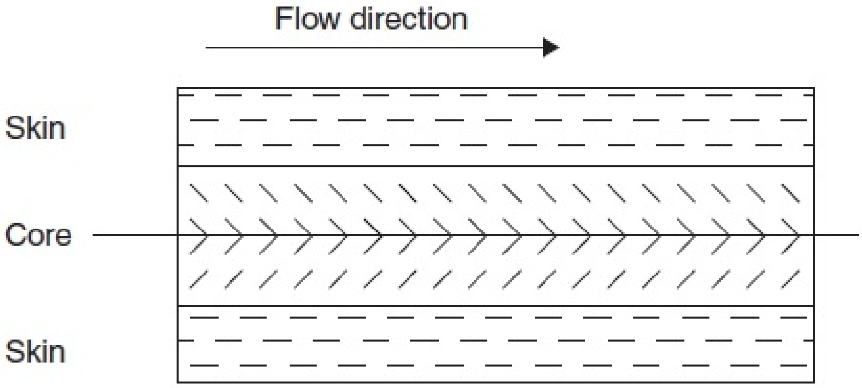
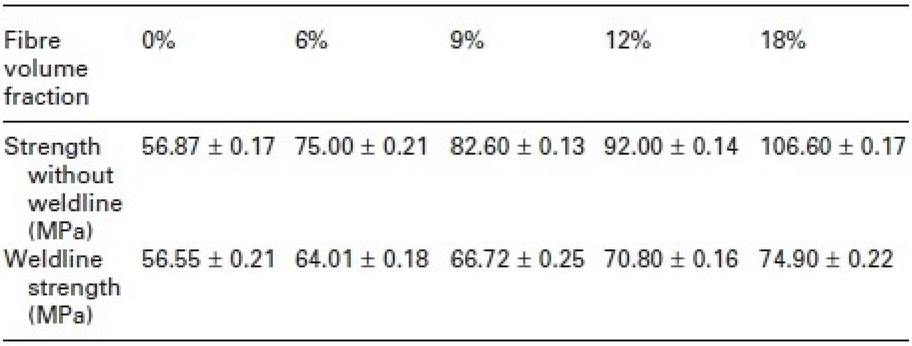


Figure 16: Fibre orientation in a injection moulded composite part [6, pg.19]

Another typical defect of injection moulding is the formation of the aforementioned weld / knit lines that appear around cavities (e.g. cores) and behind gates. Especially SFPCs with longer fibres (> 1 mm) are prone to forming weld lines. Their formation can be limited by increasing the time of injecting. Table 2 shows the effect of weld-lines on strength. It should be noted that even with weld-lines negatively affecting the strength, the composites are still stronger than just the polymer without reinforcement. [6]

Table 2: Tensile strength with and without weldlines [6, pg. 20]



Fibre volume fraction	0%	6%	9%	12%	18%
Strength without weldline (MPa)	56.87 ± 0.17	75.00 ± 0.21	82.60 ± 0.13	92.00 ± 0.14	106.60 ± 0.17
Weldline strength (MPa)	56.55 ± 0.21	64.01 ± 0.18	66.72 ± 0.25	70.80 ± 0.16	74.90 ± 0.22

Another large problem is the breakage of the fibres, which happens for the same reason as with extrusion compounding. [6]

Last but not least, it is hard to maintain dimensional accuracy during injection moulding. The parts shrink while cooling and can even warp. The fibres increase the warping, and so does differential cooling (especially on parts with inconsistent thickness). The warping can be somewhat prevented adding stiffeners and adjusting the fill time (although both too short and too long times can cause warping too). [5]

The fibres and the fillers also affect the moulding characteristics – they increase the viscosity and worsen the melting process and thus require higher pressures. [6]

The processing has a large effect on the performance of the final composite, and thus high-performance SFPC require both the right combination of matrix and reinforcement but also the right type and parameters of the injection moulding process. [6]

3.3. THERMOSET INJECTION MOULDING

The injection moulding of thermoset-based composites is mostly similar to injection moulding of thermoplastics with a few exceptions that will be described here. [5]

The only usable thermosets are low-viscosity resins that maintain the low-viscosity for a long time but cure fast afterwards. [5]

The fibres have to be shorter than 2 cm in order to be used and fillers can also be added. [5]

Differences to thermoplastic injection moulding

With thermosets the screw/plunger has to stay relatively cold (70 – 100 °C) and the moulds need to be warmed to 120 to 200 °C. The temperature control is critical with thermosets in order to prevent premature gelling of the polymer in the barrel. The screw itself is shorter and has lower compression ratios. [5]

The injection pressure is between 50 MPa and 100 MPa. [5]

Additional limitations and considerations

When phenolics are used, it is critical to vent the volatiles that form during the condensation process from the mould. [5]

The last notable limitation is to the size of the parts, which is less than 4,5 kg. [5]

3.4. SPECIAL SUBTYPES OF INJECTION MOULDING

Gas-assisted moulding

Gas-assisted moulding can be used to make hollow parts by injecting inert nitrogen gas into the hot polymer, in which the gas forms a channel. The gas is typically injected at 2,8 – 5,5 MPa. [5]

Injection compression moulding

Injection compression moulding allows for forming with a partially opened mould, which is then closed and compressed. This method limits the fibre breakage typically associated with injection moulding. [5]

Thin-wall injection

Thin-wall injection is, as the name suggests, used for parts with thin (0,5 – 2 mm) walls, that have the length : thickness ratio higher than 75. Due to the fast cooling of the thin walls the filling has to be very fast (less than ¾ of a second) and under high pressure (100 – 240 MPa). [5]

Structural foam moulding

Structural foam moulding allows manufacturing of very large parts with high strength-to-weight ratio. Parts made using this method have a solid skin and a foamed core that is created by using chemical blowing agents. [5]

3.5. SPRAY-UP

General information

The spray-up technique is best suited for low to medium volume productions and can be used to make medium to large parts. [5]

Polyesters are used for spray-up onto open tools, and the tools can also be assembled from multiple parts if needed. [5]

Description of the tools and the manufacturing process

A continuous fibre roving is fed through a combination of a chopper and a spray gun, where it is chopped and mixed with a catalyzed resin onto an open tool. The fibres are chopped to 2,5 – 7,5 mm. After the layer is sprayed, it is manually densified with rollers, which removes air and works the resin into the fibres. After this is finished, additional layers can be added, forming a laminate. After the last layer is added, the part is left to cure at a room temperature or at an increased temperature to speed up the process. [5]

A gel coat can be added to the surface to improve it. Rovings or cloths can also be placed between the layers to improve the mechanical properties. [5]

Advantages, disadvantages and other considerations

The main advantages of this method is the low cost of tooling since there is no need for a high pressure mould. The processing is also simple, and all of the equipment is portable, which allows on-site fabrication. Furthermore there is no limit to the size of the parts. The last big advantage is that the spray-up process can be easily automated. [5]

The main disadvantage is the low strength of composite parts made by spray-up. The tensile strength does not exceed 70MPa, which is caused by the limited amount of fibres (15 – 20 volume %). [5]

3.6. COMPRESSION MOULDING

General information

Compression moulding is a method that uses high pressures in matched dies. It is suitable for high volume production (over 1000 – 100 000 pieces per year) due to the larger initial investment into the tooling (e.g. dies). This method is capable of producing complex high-performance parts with good surface quality and it offers good dimensional control. Inserts or attachments can be moulded directly; hence, it eliminates the need for machining. It can be used for large parts (up to 3,7 m^2) and thicknesses as low as 1,3 mm. Compression moulding can also utilize both thermosets and thermoplastics. This manufacturing method is fairly common in the automotive industry. [5]

Description of the tools and materials

The dies are machined from a chrome-plated steel, and they are heated by steam or oil or, more rarely, by water or electrically. Dies can be fitted with a mechanism for ejecting parts after curing, either using pins or by using pressurized air to push them out. [5]

3.7. THERMOSET COMPRESSION MOULDING

Introduction

Compression moulding of thermosetbased composites uses compression moulding compounds, which are a mixture of a resin and chopped strands of fibres. It is typically supplied as sheets or bulk. A compound is placed into a matched metal mould, formed with pressure into the desired shape and then cured with heat and pressure. If complex parts are to be made preforms can also be used. The process can be observed in figure 17. [5]

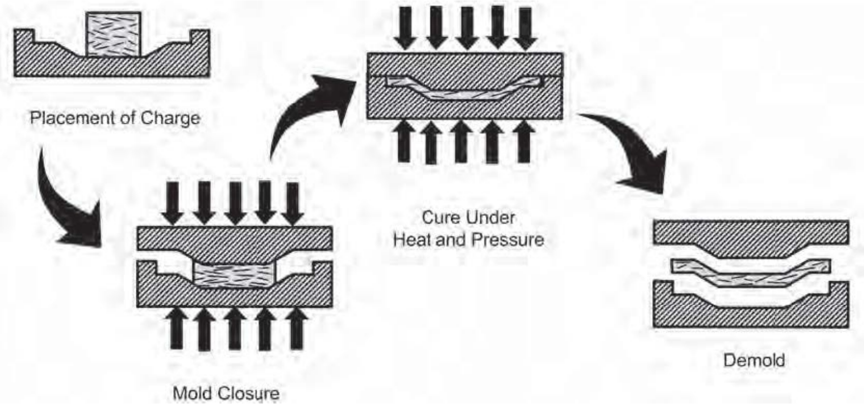


Figure 17: Thermoset compression moulding [5, pg. 290]

3.8. SHEET MOULDING COMPOUND

Description of the compound and its manufacturing

If the compound is supplied as a sheet it is referred to as a sheet moulding compound. The process for making this kind of compound can be seen in figure 18. The fibres get chopped to 2,5 – 5 cm length and are deposited onto a coat of a polymer paste travelling on a layer of polyethylene film web.

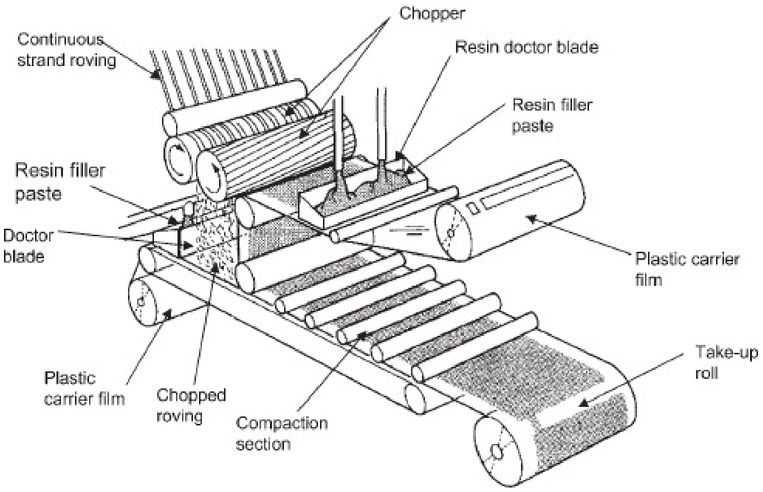


Figure 18: Sheet moulding compound machine [5, pg. 291]

Afterwards a second film with resin is added, sandwiching the fibres between 2 layers of polymer. The sheet is then rolled into a roll. The final thickness of such a sheet is around 0,5 cm and the rolls are 1 – 2 m wide. The roll is then aged in 30°C for about a week for thickening. The resulting composition is typically around 25% polymer, 25% glass fibres and 50% fillers, although, if better mechanical properties are needed, the fibre content can be as high as 65 %. [5]

Chopped strand mats can be added to improve mechanical properties and sometimes even long longitudinal strands are added. [5]

The most common type of polymer used is polyester. It also comes in a low-shrink and low-profile variants, which have, however, worse mechanical properties than the regular one. Less commonly used polymers are vinyl esters, phenolics, ureas, melamines and epoxies. [5]

The use of fillers is also common. Their main purpose in the sheet moulding compound is to minimize shrinking and to reduce the cost. Calcium carbonate, aliminium trihydrates and kaolins are used. Mould-release agents (zinc calcium) and thickeners (calcium oxide, magnesium oxide, magnesium hydroxide, calcium hydroxide) can also be added. [5]

Description of the manufacturing process

For the compression moulding of sheet moulding compound, the raw material is stacked into "charges". They are then heated with infrared light in an oven or with forced-air impingement heaters, placed into the heated mould and cured under pressure. [5]

Advantages and disadvantages

One of the greatest advantages is that there is very little excess material. There is, however, the danger of knit-line formation. It is therefore important to place the charges in a manner that prevents or limits their formation. [5]

3.9. BULK MOULDING COMPOUND

Description of the compound and its manufacturing

If the compound is supplied as bulk, it is referred to as a bulk moulding compound. It typically consists of 20% fibres 0,3 – 3 cm long, resin, fillers, catalyst and pigment. The compound is made in an extruder, and the compound leaving the extruder has a consistency of a modelling clay. It is often shaped into ropes or logs. [5]

There is a wide variety of compounds available, varying in the matrix and fibre composition. [5]

This type of compound is well suited for high-volume production and it produces parts with good finish, good mechanical properties and it offers a good dimensional stability during manufacturing. [5]

Description of the manufacturing process

During moulding, the compound is placed into a heated matched-metal die, pressed and cured. [5]

3.10. COMPRESSION MOULDING COMPOUNDS

The most common types of polymer for compression moulding compounds are phenolics, alkyds and epoxies. The typical volume of fibres in the matrix is around 40% and the fibres are around 1 mm long. The compound gets pelletized before the moulding and the pellets have a diameter of 1,5 – 6,5 cm and are 0,5 -2,5 cm long. The typical curing pressure is 5 – 20 MPa and temperature between 170 °C and 190 °C. It is a common practice to postcure the parts to increase their resistance to high temperatures. [5]

3.11. PREFORM

Description of the compound and its manufacturing

Preform is another kind of ready-to-mould compound for manufacturing SFPC. The preform is a mat of chopped fibres that are held together by a binder. This allows the preform to have approximately the shape of the final part. Preforms are used for large parts with constant cross sections and the percentage of reinforcing fibres is typically very high.

There are two methods for forming preforms – direct fibre method and plenum chamber method. [5]

With the direct fibre method, continuous fibres are chopped to 2,5 – 5 cm and blown with the binder onto a rotating screen that has the approximate shape of the final part. The fibres are held on the screen by suction until the preform's binder is set in an oven.

The plenum chamber method is similar to direct fibre method but the fibres and binder are blown into an air chamber where they are sucked onto a rotating screen. [5]

The process of spraying the fibres and binder onto the screen can be seen in figure 19.

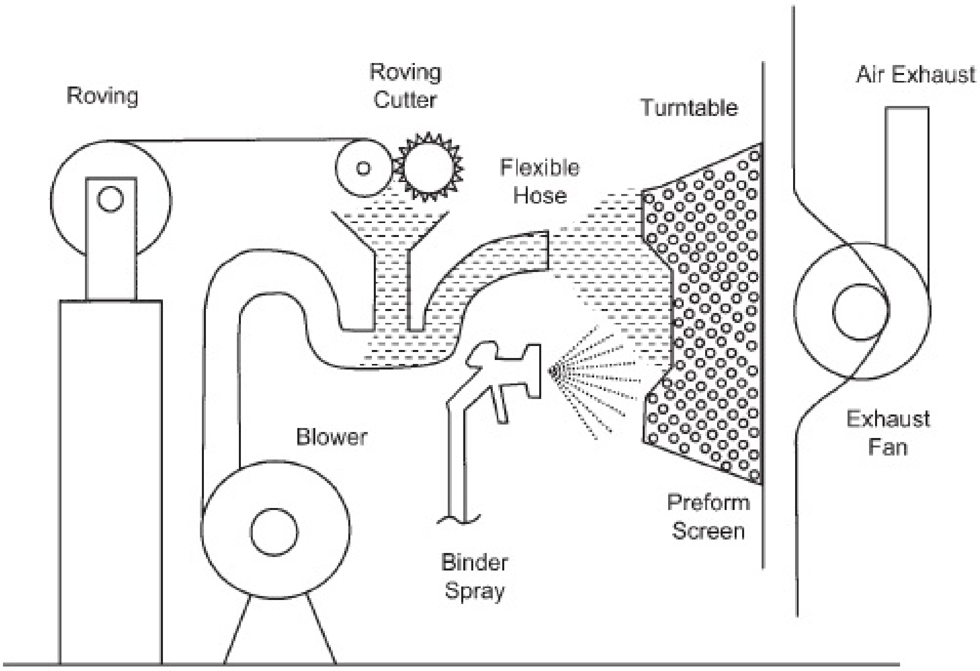


Figure 19: Spraying fibres onto rotating screen [5, pg. 294]

Description of the manufacturing process

After the preform cures it is ready to be placed into the die, into which the resin is added, and cured. [5]

During the compression moulding the two halves of the die are heated to 105 – 160 °C and pressurized to 1 -14 MPa (higher fibre content requires higher pressure to ensure wetting of the fibres). The curing itself typically takes 1 – 5 minutes. In the case of condensating resins (phenolics), volatiles are formed and need to be vented. This is accomplished by opening the die momentarily. [5]

It is possible to create hollow parts using this method by using cores from low-melting metals that are melted out after curing. [5]

3.12. TRANSFER MOULDING

General information

Transfer moulding is similar to compression moulding, but it also incorporates some elements from injection moulding. It is used for manufacturing very small and very complex parts thanks to good dimensional control and tolerances. The typical amount of the reinforcing phase is 10 – 35 %. [5]

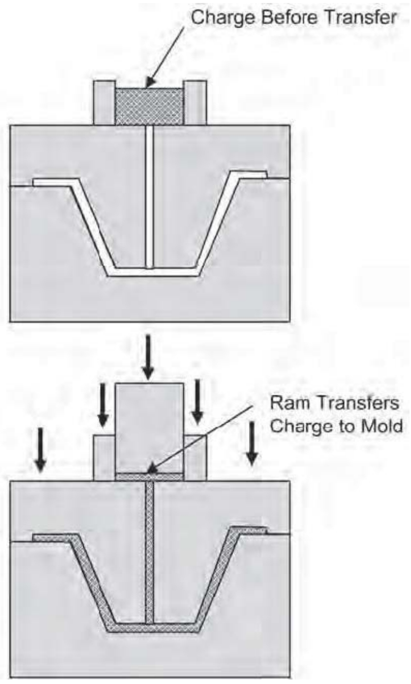


Figure 20: Transfer moulding [5, pg. 296]

Description of the manufacturing process

The compound is heated to 150 – 180 °C in a separate chamber from which it is then pushed by a ram into the mould. A schematic of the process can be seen in figure 20. [5]

3.13. GLASS MAT THERMOPLASTIC COMPRESSION MOULDING

General information

Glass mats are made of either continuous or chopped glass fibres and polypropylene. Unidirectional mats are also used. The typical fibre content is around 40%. [5]

This method is popular in the automotive industry because it is fast and can be automated. [5]

Description of the manufacturing process

The material is reheated by infrared heat banks to 320 °C before it is hydraulically pressed in the mould, which is preheated to 135 °C, and left to solidify. The pressure inside the mould is 7 – 28 MPa. Two-stage compression is often used with the first stage being fast and the second one slower so that the material can properly fill the mould. [5]

3.14. LONG DISCONTINUOUS COMPRESSION MOULDING

General information

The long-fibre thermoplastic process works with a polypropylene matrix. The fibres are 12, 25 or 50 mm long. Although the fibres are long, they are discontinuous; therefore, this manufacturing technique is more similar to SFPC manufacturing. For this reason I have decided to include it even though the resulting composite is not a short-fibre composite by some definitions. [5]

The long discontinuous thermoplastic process can be highly automated and is faster than the glass mat thermoplastic process. [5]

Description of the manufacturing process

The polymer is molten in the extruder. At the end of the extruder the fibre is added, which ensures good impregnation. Is is then directly moved to the pressing machine without any additional reheating, which leads to reduced cycle time. [5]

3.15. ADDITIVE MANUFACTURING (3D PRINTING)

General information

Similarly to other materials, additive manufacturing has started appearing as an option for manufacturing short fibre polymer composites. Most additive manufacturing processes for polymers can be used for short fibre composites. Only some methods of additive manufacturing have been successfully used for manufacturing SFPC, but due to the fast development of additive manufacturing more are sure to follow. [8]

Advantages

Additive manufacturing allows more freedom in design, namely very complex “cellular” shapes, which are starting to appear more regularly thanks to topological optimization. Some methods allow fibre alignment. Another big advantage is that additive manufacturing can be used for rapid prototyping, since additive manufacturing does not require expensive moulds. [8]

3.16. EXTRUSION-BASED ADDITIVE MANUFACTURING

This method works with the composite material in liquid form and it is a layer-by-layer process. It typically works with thermoplastic filaments, viscous hydrogel or viscoelastic inks of thermosets. There is a wide variety of printing heads – each for a different material. [8]

The quality of the resulting part depends on the feeding speed, the melting temperature, the chemical composition of the fibre-polymer mixture and the distribution of fibres. [8]

Fused filament fabrication (FFF)

In this method a thermoplastic filament is melted and fed to a heated nozzle from which it is then extruded in layers onto a deposition bed. The extrusion happens under high pressure so that flow of molten composite is maintained and warping is prevented. Support structures, which are to be removed after the part is finished, can also be used. [8]

Polymers commonly used for fused filament fabrication are PLA, ABS, polychloride, polystyrene, nylon, PAEK, PPS and PPSV. [8]

FFF is by far the leading method for manufacturing SFPC. [8]

Direct ink writing and reactive extrusion

This relatively new method uses a reactive liquid polymer, which cures immediately under UV light or with use of heat. Fibres are added for increasing the viscosity rather than improving the mechanical properties. Photocurable acrylic base resins and thermal curable epoxies are used with carbon or glass fibres. Fumed silica or nanomaterials, such as carbon nanotubes, can also be used. [8]

Large scale extrusion based processes are not yet common, but there is a great potential and they are being developed. [8]

3.17. POWDER-BASED ADDITIVE MANUFACTURING

Carbon based processes use a powder that is selectively sintered. Fibres used in this group of processes are carbon, ceramic or metallic. [8]

Selective laser sintering

Selective laser sintering is a powder-bed fusion process, during which a CO_2 laser selectively fuses thermoplastic powder together. [8]

Polyamide, PAEK, PP and PE are used along with nanofillers, which work as a flow agent, and short fibres, which reinforce the composite. [8]

However, experiments have shown that only a minor improvement of mechanical properties can be gained and in some cases the mechanical properties of the final part are worse than those of just the polymer. This is most likely due to poor adhesion between the fibres and the matrix. [8]

Multiple jet fusion

This layer-by-layer method fuses powder together through IR light and dispersion of fusion and antifusion powders. The fusion powder helps with absorbing the energy from the infrared light and the antifusion powder prevents it. [8]

PP and polyamides are suitable for this method. [8]

3.18. PHOTOPOLYMERIZATION-BASED ADDITIVE MANUFACTURING

This method works with UV curable polymers such as epoxies and acrylic resins. These polymers have good wetting characteristics and the are very flowable. [8]

Photopolymerization based processes offer high dimensional accuracy if strict manufacturing conditions are met. This is, however, hard to achieve, and stable manufacturing of high-performance composites is not possible yet. [8]

VAT Polymerization

This sub-group consists of three methods – stereolithogrpahy, digital light process and continuous liquid interface production. [8]

Stereolithography works with UV light, which is controlled with a lens, allowing for selective curing of the polymer. [8]

Digital light process, on the other hand, cures the polymer layer-by-layer and also works with long fibres. [8]

The last progressive method is continuous liquid interface production. With this method oxygen is kept between the liquid and solid, which accelerates the curing process and leads to superior polymerization. [8]

3.19. SUMMARY AND COMPARISON OF MANUFACTURING METHODS

In this subchapter all of the reviewed manufacturing methods and are compared (table 3). Please note that additive methods are omitted since their use is not common in commercial applications and not enough information is available yet.

Table 3: Comparison of SFPC manufacturing methods

Method	Advantages	Disadvantages	Mechanical & other properties
Injection moulding	• Large scale production • Little processing • Inexpensive manufacturing process • Special types for large parts, thin wall parts, hollow parts • Fibre alignment can be controlled	• Expensive tooling • Sensitive to temperature • Hard but good dimensional control • Inhomogenous structure • Risk of weld-lines • Damaged and short fibres	• Fibre length: 0,8 to 3 mm • Fibre volume fraction: <45 % • Cycle time: 20 – 120 s • Strength: variable and relatively low due to low fibre length
Spray-up	• Low cost of tooling • Allows for on site fabrication • No size limit • Can be automated easily	• Low strength • Does not allow for fibre alignment	• Fibre length: 2,5 – 7,5 mm • Fibre volume fraction: 15 – 20 % • Cycle time: variable (depending on part) • Strength: <70 MPa
Compression moulding	• Large scale production • Good surface quality • High performance parts	• Expensive tooling • Danger of knit line formation (only some compounds)	• Fibre length: variable, dependant on compound type 0,3 – 5 cm

	• Wide variety of moulding compounds → variety of final properties • Longer fibres (order of magnitude of cm) • Can use aligned fibre mats • Good dimensional control • Little excess material		• Fibre volume fraction: <60 % (dependant on type of compound) • Cycle time: variable (depending on part) • Strength: variable (depending on type of compound), if aligned fibre mats are used up to 1500 MPa

4. IMPROVING THE MECHANICAL PROPERTIES OF SHORT FIBRE COMPOSITES

4.1. INTRODUCTION

Short fibre composites have one major drawback – their mechanical properties. They are typically much less strong than long fibre composites. SFPC could, however, reach up to 90 % of the strength of their long fibre counterparts through alignment of fibres. Aligning the fibres can also mitigate problems with brittleness, which is typical for some polymer types (e.g. epoxies). [9]

There are several methods used for orienting the fibres uniformly in the composite, it should, however, be noted that most of the methods are not used commercially on a large scale and with many of them it is quite unlikely they will ever become feasible for larger scale use due to prohibitive costs, long production times or low effectiveness. [9]

The processes can be divided into wet and dry processes, depending in whether flow of a liquid is used or not. Dry methods are typically quicker but less effective at aligning the fibres. [9]

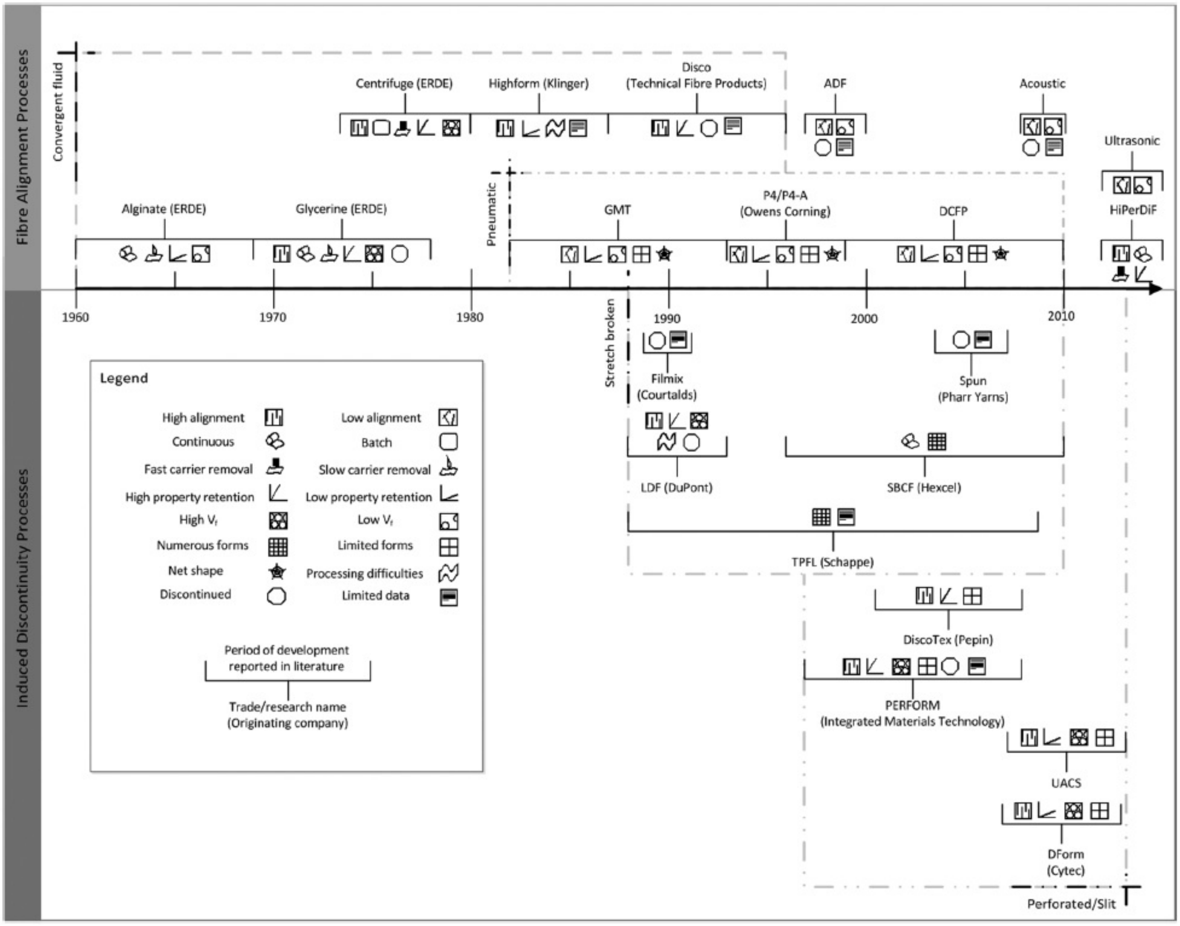
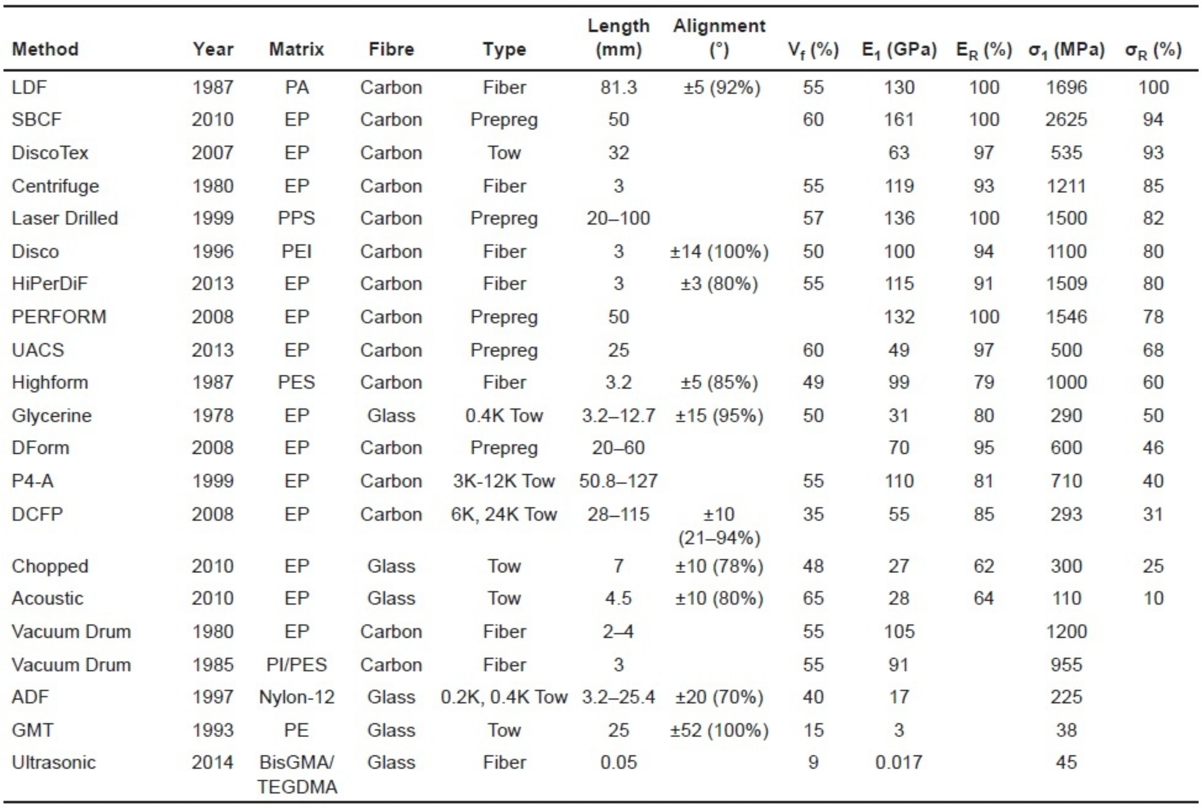


Figure 21: Timeline and properties of alignment methods [10, pg. 162]

This chapter will describe these methods and analyse why they are likely not going to expand or why they may become used more commonly in SFPC production. The methods will be described in groups based on the principle of the method rather than the exact type as seen in figure 21.

It should also be noted that comparing these methods is hard. Each experiment/research works with different materials and the history of improving SFPC's properties dates back to the late 60s. Figure 21 shows the timeline of the improvement methods along with additional details regarding the level of fibre organization, the strength, its being in use, etc. It should, however, be said, that there are more methods than listed, some of which, such as additive manufacturing, are described later. In table 4 a comparison of the basic properties of parts made using some of the methods can be seen. [10]

Table 4: Comparison of methods for aligning short fibres [10, pg. 163]



Method	Year	Matrix	Fibre	Type	Length (mm)	Alignment (°)	V_f (%)	E_1 (GPa)	E_R (%)	σ_1 (MPa)	σ_R (%)
LDF	1987	PA	Carbon	Fiber	81.3	±5 (92%)	55	130	100	1696	100
SBCF	2010	EP	Carbon	Prepreg	50		60	161	100	2625	94
DiscoTex	2007	EP	Carbon	Tow	32			63	97	535	93
Centrifuge	1980	EP	Carbon	Fiber	3		55	119	93	1211	85
Laser Drilled	1999	PPS	Carbon	Prepreg	20–100		57	136	100	1500	82
Disco	1996	PEI	Carbon	Fiber	3	±14 (100%)	50	100	94	1100	80
HiPerDiF	2013	EP	Carbon	Fiber	3	±3 (80%)	55	115	91	1509	80
PERFORM	2008	EP	Carbon	Prepreg	50			132	100	1546	78
UACS	2013	EP	Carbon	Prepreg	25		60	49	97	500	68
Highform	1987	PES	Carbon	Fiber	3.2	±5 (85%)	49	99	79	1000	60
Glycerine	1978	EP	Glass	0.4K Tow	3.2–12.7	±15 (95%)	50	31	80	290	50
DForm	2008	EP	Carbon	Prepreg	20–60			70	95	600	46
P4-A	1999	EP	Carbon	3K-12K Tow	50.8–127		55	110	81	710	40
DCFP	2008	EP	Carbon	6K, 24K Tow	28–115	±10 (21–94%)	35	55	85	293	31
Chopped	2010	EP	Glass	Tow	7	±10 (78%)	48	27	62	300	25
Acoustic	2010	EP	Glass	Tow	4.5	±10 (80%)	65	28	64	110	10
Vacuum Drum	1980	EP	Carbon	Fiber	2–4		55	105		1200	
Vacuum Drum	1985	PI/PES	Carbon	Fiber	3		55	91		955	
ADF	1997	Nylon-12	Glass	0.2K, 0.4K Tow	3.2–25.4	±20 (70%)	40	17		225	
GMT	1993	PE	Glass	Tow	25	±52 (100%)	15	3		38	
Ultrasonic	2014	BisGMA/ TEGDMA	Glass	Fiber	0.05		9	0.017		45	

Note: V_f – fibre volume percent, E_1 – Young's modulus, E_R – stiffness retention accounting for different fibres and matrices, σ_1 – tensile strength, σ_R - tensile strength retention accounting for different fibres and matrices

4.2. ELECTRICAL FIELD METHODS

Electrical methods work by inducing forces on fibres with an external electric field. There are both dry and wet methods. Both AC and DC sources can be used. [9]

Principle

The electrical field induces a dipole moment on the fibre in the liquid matrix. „*When a rod (e.g. single SCF) is suspended in a dielectric liquid (e.g. a liquid epoxy resin) and then subjected to an AC electric field, the rod becomes polarised due to its shape anisotropy, dielectric properties and electrical conductivity being different to that of the liquid resin. As a result, a greater density of opposing charges will be induced at the ends of the rod. The interaction of this dipole with the electric field gradient during the dielectrophoresis process generates a torque; which leads to rotation and alignment of the SCFs in the direction of the applied electric field.*“ [11, pg. 15]. The force exerted on the fibre is stronger than forces with centrifugal alignment. [12]

Advantages

Electrical field methods can act locally and work with any composite. Theoretically by optimizing the shape of the electrode a certain pattern could be created but I was not able to find any experiments confirming this. [12]

Experiment 1

First experiment was aimed at describing the microstructure of a composite aligned with an electric field. In this experiment glass fibres (20 µm diameter, 0,25 – 1,25 mm long) were used at 10 volume %. They were suspended in an uncured epoxy and aligned with electric field (f = 5 Hz, E = 1,2 – 2,4 kV/mm for orthotropic composite). [12]

Results & evaluation of experiment 1

The experiment showed that the time to rotate the fibre is independent of the fibre aspect ratio. As expected, the resulting material was stronger and reached 40,4 MPa at 10 volume % of the reinforcing phase. The accuracy of alignment was not given [12]

Experiment 2

The purpose of this experiment was to improve the fracture toughness of epoxies. Its results are, however, also relevant to improving the mechanical properties of SFPC. [11]

The fibres (7 µm diameter, 1,8 – 3,5 mm) were mixed with the polymer to 10 weight %. During mixing the average fibre length was reduced to 0,72 mm. The mixture was then further diluted to 5; 2; 1,5; 1 and 0,5 weight %. The epoxy-fibre mixture was then poured between the electrodes and aligned by electric field (E = 30 V/mm, f = 10 kHz). [11]

Results & evaluation of experiment 2

The length and the aspect ratio had once again no influence on aligning glass fibre above certain electric field intensity and aspect ratio. [11]

The alignment process was heavily influenced by the amount of the reinforcing phase. At 0,5 weight %, 55 % of the fibres were within 30 degrees of the ideal orientation. The amount of aligned fibres decreased rapidly with higher weight percentage.

Due to the low volume fraction this method is not useful for high-performance application. The processing time was also very long (1 hour). [11]

4.3. MAGNETIC METHODS

General description

This group of methods is relatively similar to the electric ones both in principle and in the results. [13]

Magnetic force is a contactless volume force. In most experiments a homogenous field was used and the fibres rotated in one place (there was no displacement). [13]

Magnetic methods are highly sensitive to the magnetic properties of the fibres and like all wet methods to the curing rate and viscosity of the matrix, all of which affect the effectivness of the method. [13]

One interesting result of the experiments was the fact that the alignment happens faster with longer fibres (nickel coated carbon fibres). Those also require magnetic field intensities since the magnetic susceptibility of a longer fibre is higher than that of a short fibre. A graph highlighting this effect can be seen in figure 22. [13]

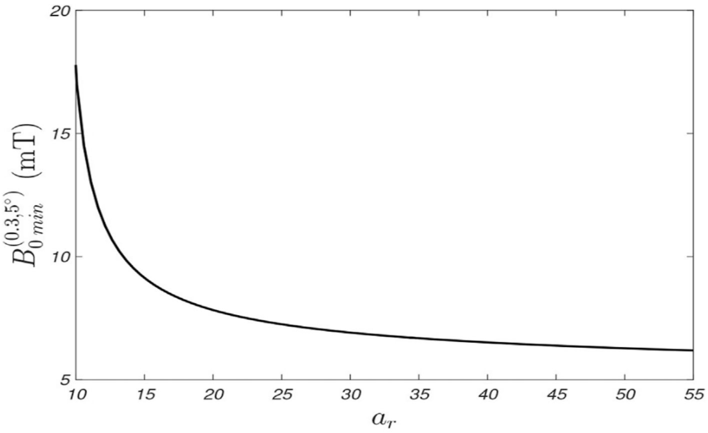


Figure 22:Relation of minimum magnetic field required to fibre aspect ratio, a_r – aspect ratio, $B_{0min}^{(0.3,5^\circ)}$ – minimum magnetic field necessary to have 30 % of the fibres oriented at ±5 degrees [13, pg. 136]

Advantages

Because magnetic force is a contactless volume force, it does not damage the fibres or cause chemical alterations. It also allows for remote orientation of fibres in 3 dimensions. Another advantage is that permanent magnets and electromagnets are readily available and magnetic methods are less sensitive to changes in pH and surface than the electrical one. [13]

Disadvantages

This method is mostly used for nano-particles and carbon nanotubes. While nanotubes would improve the mechanical properties of traditional composites and be a good reinforcing phase, it is currently not a common practice to use them in such a way. Furthermore, I was not able to find any studies using magnetic method for aligning fibres with the goal of improving the mechanical properties, although, it should theoretically be possible. I also was not able to find any experiment in which a higher weight percentage than 5 % would be used and with fibres longer than 0,1 mm, which makes magnetic method fairly ineffective in comparison to other methods for aligning fibres in high-performance structural composites. [13,14]

4.4. PNEUMATIC METHODS

Pneumatic process is a dry process. These processes are used mainly manufacturing glass-mat reinforced thermoplastics. [9]

Description of the manufacturing process

During pneumatic fibre alignment a mixture of fibres and polymer powder is blown from a tube onto plates and then falls onto a perforated plate. Afterwards it is heated, which forms the final glass-mat reinforced thermoplastic, which can then be used in compression moulding. The process can be seen in figure 23. [9]

Evaluation

Pneumatic methods have the worst effectivity of the "conventional" methods for aligning short fibres, with only slightly more than a half of the fibres being within 52° from the intended orientation, leading to only a minor increase in strength. [9]

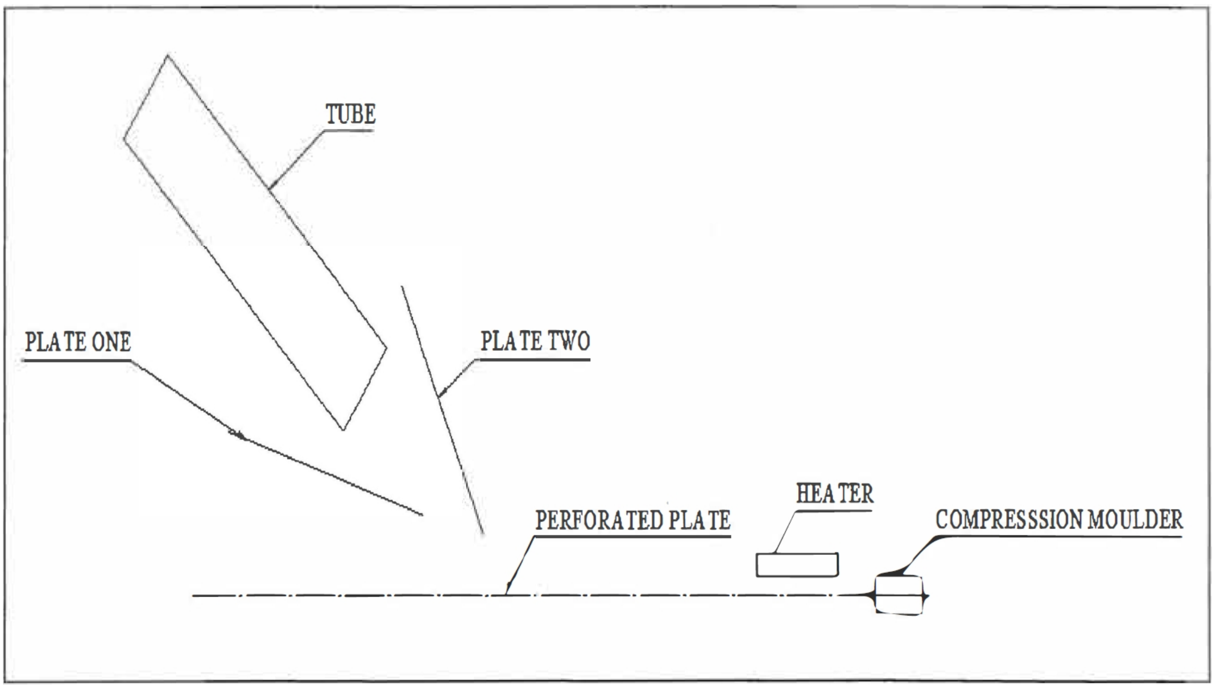


Figure 23: Pneumatic manufacturing process [9, pg. 618]

4.5. ALIGNING FIBRES IN A FIBROUS MASS

With this method a mass of fibres (2) is placed onto a screen above (3) a nozzle (4). Pulsating gas jet from the nozzle combined with low pressure gas coming from the opening in the middle (7) of the apparatus separates the fibres and lifts them upwards. When the fibres pass around the specially designed conical annular vertical passage (10), they align themselves and then they are deposited on the top of the apparatus on a porous closure (12). The apparatus can be seen in figure 24. [9]

4.6. HYDRODYNAMIC METHODS

As was already mentioned, the fibres have a tendency to orient themselves when they flow at a high speed through a narrow gate. This set of methods uses this principle to deliberately orient the fibres in the flow direction. [9]

Due to the nature of this method it is a wet method, meaning that the fibres are dispersed in a liquid. The liquid is typically highly viscous (except for water) as this ensures good fibre dispersion and alignment. The downside of viscous liquids is that the manufacturing process is slow. Glycerine, ammonium alginate but also water can be used. [9]

There are 3 general steps to all hydrodynamic methods:

- fibre dispersion preventing fibres from interacting with each other
- fibre alignment
- fast and careful separation of the liquid so that fibres are not disturbed

One minor problem is that the first two steps work best with a viscous liquid and the last step would benefit from a liquid with low viscosity. [9, 16]

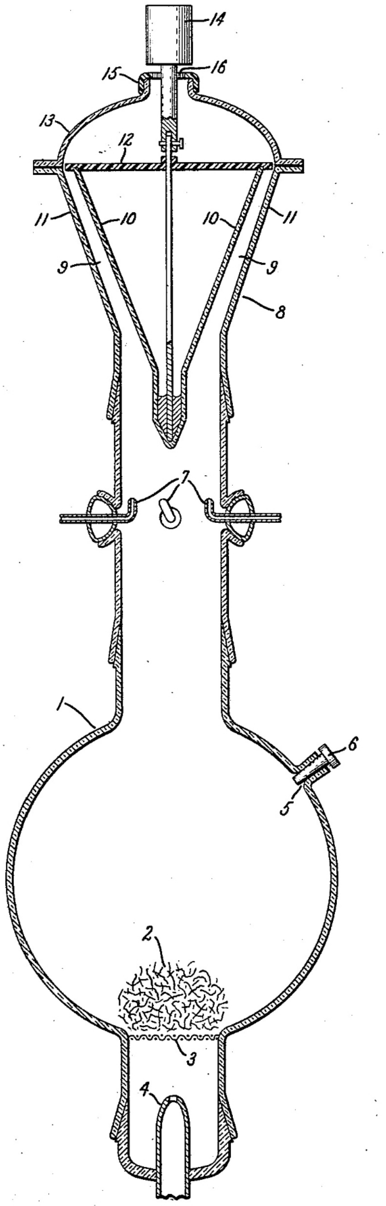


Figure 24: Annular apparatus [15, pg. 1]

4.6.1. AMMONIUM ALGINATE ALIGNMENT

Ammonium alginate is used for composites with whiskers and short fibres. [9]

The mixture is extruded through an opening into an acid precipitating bath forming gel filaments which are then dried. [9, 16]

There is no report on the alignment effectivity. This method is expensive, limited in materials, there is no possibility of recycling and the volume fraction is low. [16]

4.6.2. GLYCERINE ALIGNMENT

Glycerine is used only for short fibres. Glycerine has lower viscosity than ammonium alginate, which leads to higher productivity. [9]

Manufacturing process

The mixture of glycerine and fibres is forced through a tapered nozzle, which aligns the fibres because of the fluid friction between the boundary and the core layer. The mixture is then deposited onto a flat gauze or mesh. The carrier liquid is then removed. Since this is the longest part of the process, the removal can be sped up by application of heat. Then the fibres get washed gently by a water spray and then get impregnated. [9, 16, 17]

Results and evaluation

More than 90 % of the fibres were within ±15°. It also allows for high volume fraction of the reinforcing phase. This should make this method suitable for higher performance applications. Like most wet methods, the processing time is quite long, which may be preventing a widespread use. [17]

4.6.3. CENTRIFUGAL ALIGNMENT

This method utilizes centrifugal forces for the removal of the liquid. A fibre-liquid suspension is discharged from a nozzle onto the inner surface of a rotating permeable drum. The centrifugal force removes the liquid almost immediately resulting in good alignment of the fibres thanks to the low time when the aligned fibre is suspended in the liquid. Vacuum drums can be added for even better results. The resulting material is an aligned fibre mat. [9]

Advantages

The main advantage of this approach is the easy removal of the liquid. Resulting alignment accuracy is ±3° of around 60% of all fibres, making it a much more effective method than all dry methods. [9]

Disadvantages

The main disadvantage is that this is a batch method. [9]

4.6.4. SHEAR CONTROLLED ORIENTATION IN INJECTION MOULDING

Shear controlled orientation in injection moulding uses the interactions between the layers of the composite during injection so that the fibres align and weld line formation is suppressed. Because the part is stronger, it can be ejected sooner, which also shortens the processing time [9]

Principle

The fibres have a natural tendency to orient themselves parallel to the flow near the walls of the mould but in the middle this effect is less pronounced if at all present. A shear flow between the boundary and the middle layer helps align the fibres in the middle. [9]

The controlled macro shears are created by a device consisting of small oscillating pistons. This device in a variant with 2 piston oscillating 180° out of phase can be seen in figure 25 and version with 4 pistons oscillating 90° out of phase in figure 26. [18]

The effectiveness of this method is not reported and neither is whether it is used anymore. [18]

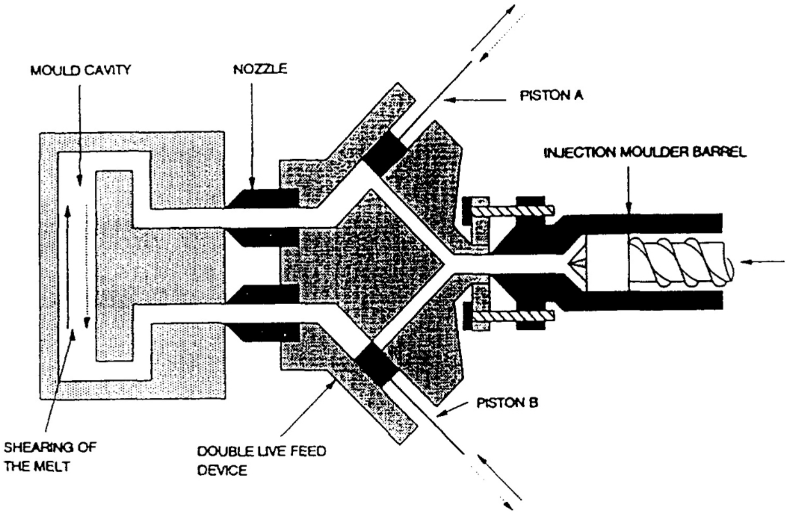


Figure 25: Double feed (2 pistons) [18, pg. 273]

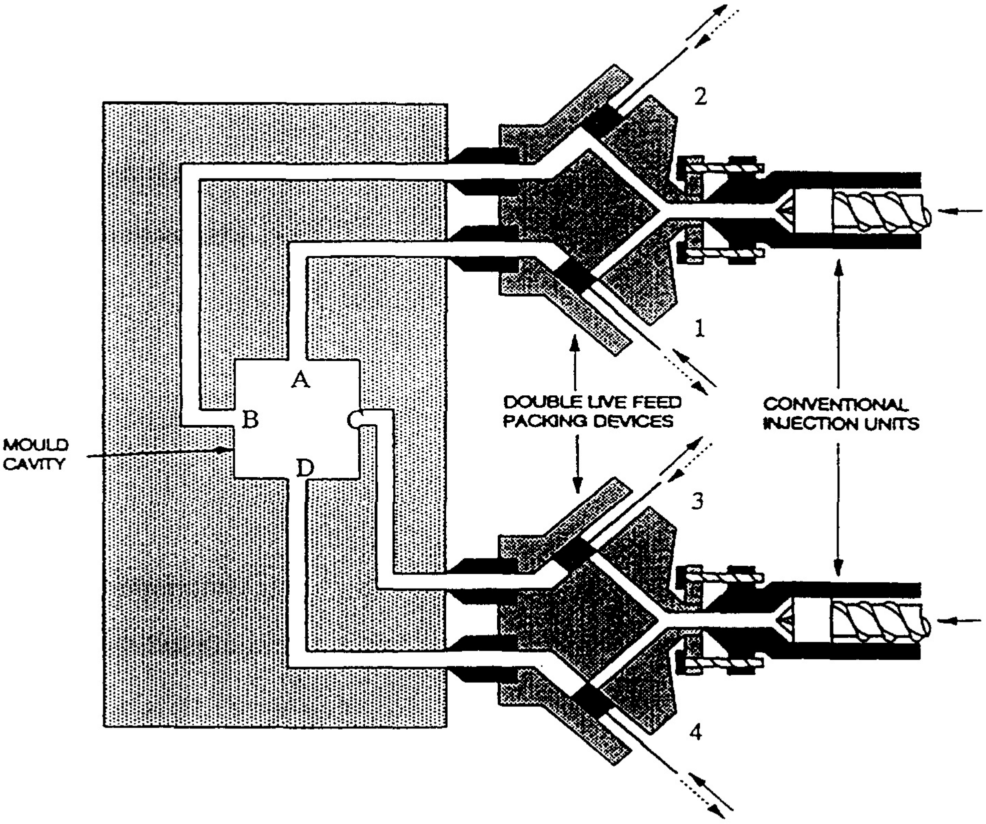


Figure 26: Quadruple feed (2 + 2 pistons) [18, pg. 273]

4.6.5. High performance discontinuous fibre method (HiPerDiF)

This relatively young method is used for producing tape or tow type prepregs of fibres less than 5 mm long. This method uses water, which is much less viscous than glycerine used with other hydrodynamic methods, as the carrier liquid. This leads to shorter production time, which is the main issue with other hydrodynamic methods. [19]

The tool

The alignment happens in a device consisting of a nozzle and two plates. The first plate orients the fibres and the other one prevents overflow. The original concept utilized plates oriented at an angle but further development changed this arrangement to the desks being parallel (figure 27). The desks need to be closer than the length of the fibre. This evolution of the method also allowed the use multiple nozzles at once for higher production rates (figure 28). [19]

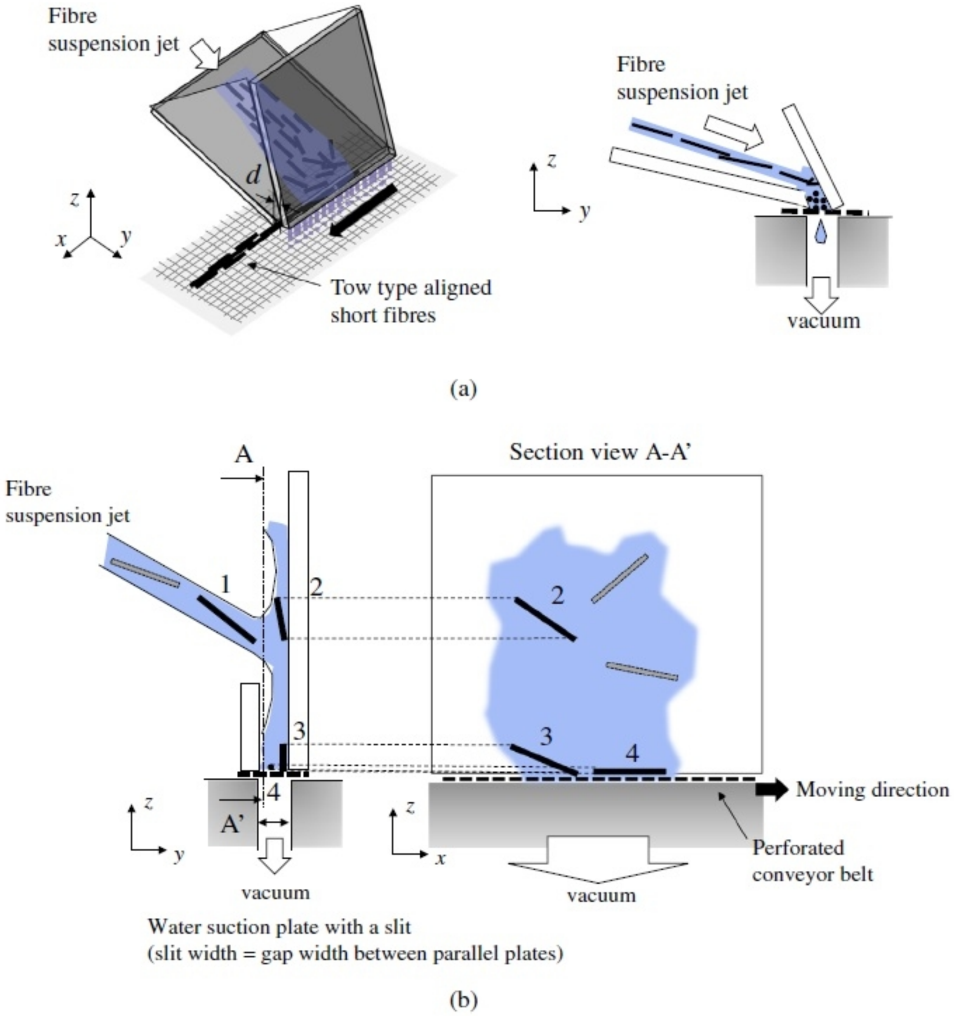


Figure 27: Schematic of HiPerDiF tooling. (a) initial design, (b) simplified design [19, pg. 177]

Principle of the method

HiPerDiF uses the change of momentum of the liquid to rotate the fibres and orient them in the desired location, hence it allows for water as the carrier liquid. [19]

Manufacturing process description

First the fibres are dispersed in the water. Then the water-fibre mixture is accelerated through a nozzle which is aimed at the orientation plate in the orientation mechanism onto which it shoots the mixture. When the fibres hit the orientation plate they are already partially aligned from the nozzle and after hitting it they turn perpendicular to the original flow direction and are then deposited onto a perforated belt. The water is then removed by suction. The fibres are then impregnated. [19]

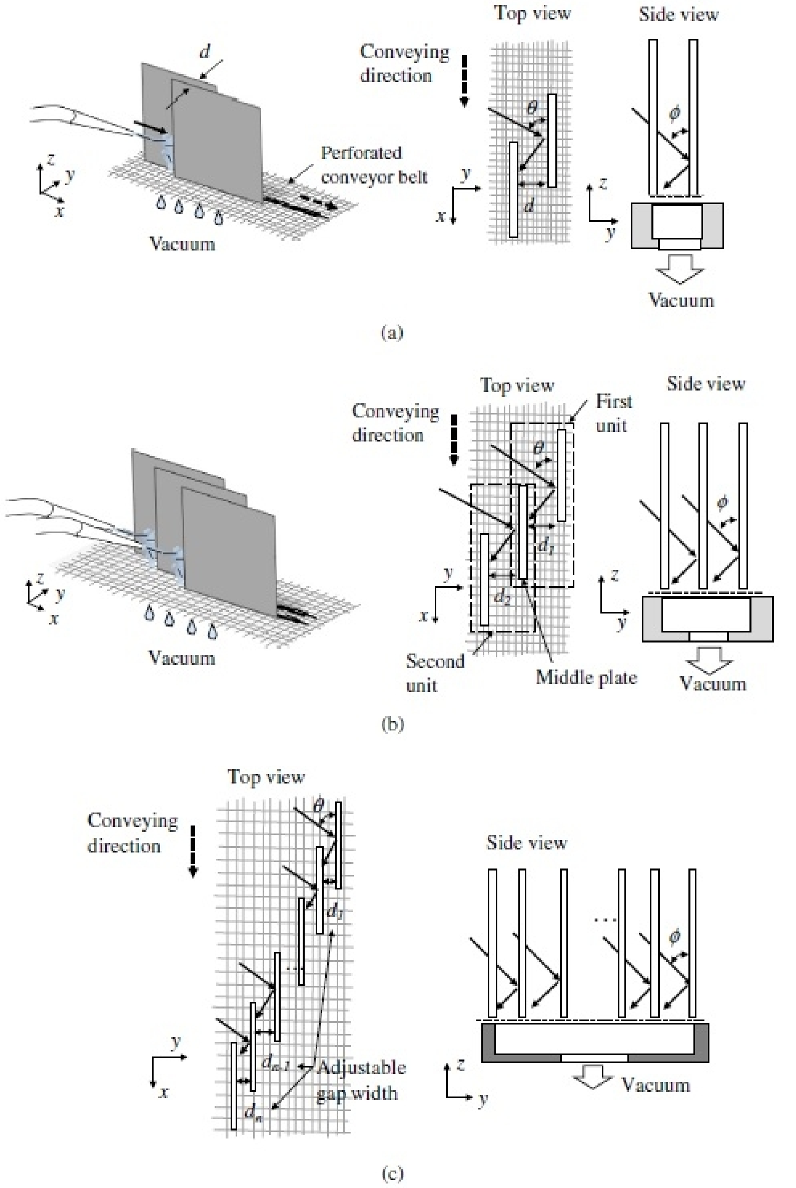


Figure 28: Use of multiple nozzles with the updated design. (a) single nozzle, (b) two nozzles, (c) multiple nozzles [19, pg. 178]

Experiment description

In the experiment testing the HiPerDiF method, Yu et al. combined carbon fibres (density: 1,820 g/cm^3, length: 3 mm, diameter: 7 μm) with a water soluble polymer and water. The fibres made 0,003 % of the mixture and the goal was two composite materials, one with volume fractions of 46 and the other one with 65 %. [19]

The manufacturing process started with HiPerDiF alignment. The prepregs made were then placed in a semi-closed mould with a vacuum bag and placed into autoclave, where they were cured at 0,69 MPa. The mould was then closed and the composite cured at 2,15 MPa and 135°C for 90 minutes. [19]

Results & evaluation

The resulting materials had fibre volume fractions of 41 and 55%, lower than expected. This was blamed on excess resin and misaligned fibres. The orientation of the fibres was much better than expected though. 65% of fibres were within 3° in the specimen with 41% of fibre volume fraction and 67% of the fibres were within 3° in the specimen with 55% of fibre volume fraction. Furthermore even with relatively low moulding pressures the fibre packing was good, leading to high tensile modulus and strength, 115 GPa and 1509 MPa respectively for the specimen with 55% of fibre volume fraction. A comparison of the properties of a composite made using the HiPerDiF method to other aligned short fibre composites as well as continuos carbon epoxy composite can be seen in figure 29. [19]

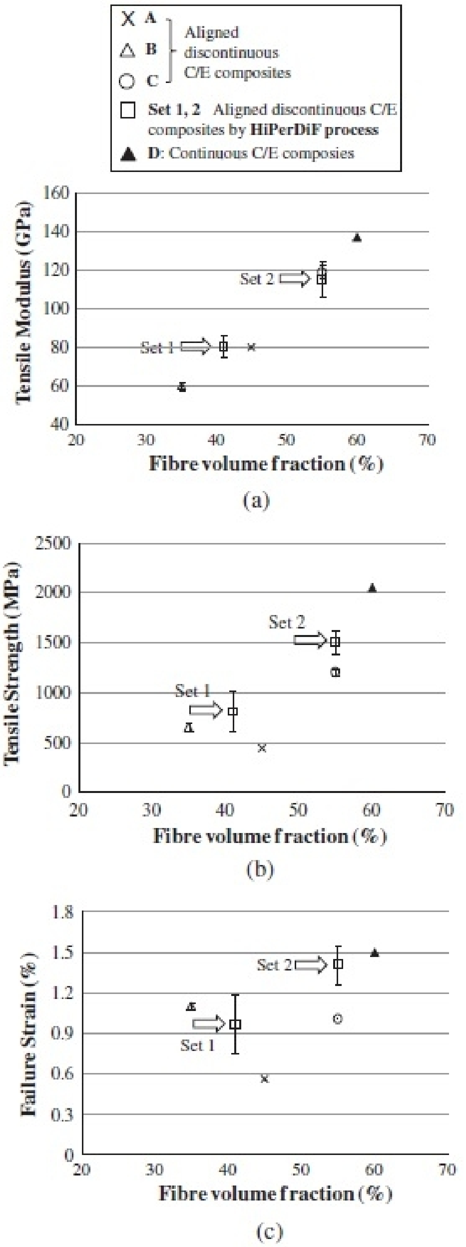


Figure 29: Comparison of (a) tensile modulus, (b) strength and (c) strain for HiPerDiF made specimens and existing experimental data (see legend above) [19, pg. 184]

It should also be noted that there are similar methods but all of them achieved worse results in terms of mechanical properties than HiPerDiF, which appears to be the best method for aligning short fibres to date. [19]

4.7. ULTRASONIC METHODS

A method using a completely different approach to the previous ones is the ultrasonic method. The alignment of the fibres happens as a response to standing sound waves. The fibres align to the nodal positions of the waves. [20]

There are several approaches – mode switching, focused ultrasonic beams, linear arrays of transducers facing a reflective surface and emission of counter propagating waves. The last one is less sensitive to changes of the resonant frequency because of the particle content and the position of the nodes can be changed. [20]

Similar to other wet methods, the viscosity of the liquid phase is critical (lower is better). [20]

Experiment description

There were several experiments with ultrasonic alignment, one of which wanted to determine the improvement of mechanical properties of a composite with its fibres aligned by ultrasound. In this experiment glass fibres were used (50 µm long, 14 µm in diameter). Standing waves were created by two opposing transducers. Figure 30 shows the entire apparatus including cooling water and PMMA dividers keeping the transducers and resin apart. The fibres were placed on a substrate, the resin was than added and the ultrasonic field moved the fibres to the nodal positions. Then the composite was cured. The resulting material was cut into smaller specimens. [20]

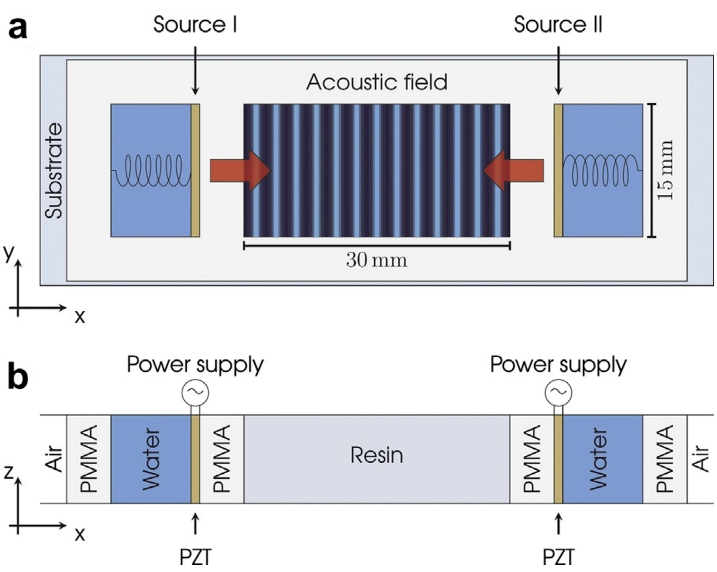


Figure 30: Ultrasonic apparatus [20, pg. 1016]

Results & evaluation

The fibre volume fraction was 9 % ±2 %. The measurements confirmed an increase in stiffness in the direction of alignment (8% better than transverse to the direction) and up to 43% improvement of strength even though the volume fraction of the reinforcement was so low. [20]

The experiment was, however, done on a thin sample with just one layer. Furthermore there are no mentions about the accuracy of alignment and possibility of increasing the low volume fraction and the length of the fibres. It is also not clear if this method could ever be used for a large scale manufacturing. There has been research into the effects of ultrasound onto a single fibre but very little research has been made for a mass of fibres. Ultrasonic methods are therefore at this point unlikely to be used commercially for aligning the fibres in SFPC. There is, however, the possibility of using them in additive manufacturing, which is currently being researched. [20]

4.8. ADDITIVE MANUFACTURING

3D printing is an even less conventional method that can create composite parts with aligned fibres. Unlike other methods, many of which have first appeared as soon as in the 70s and never caught on, 3D printing is relatively young and still evolving rapidly. [20]

The best results in terms of mechanical properties were achieved using a combination of carbon fibres and a thermoplastic. There were two similar experiments of fibre alignment in fused deposition modelling (more accurately fused filament fabrication (chapter 3.16.)), only differing in fibre volume fraction and therefore also the resulting mechanical properties. In the following, the experiment with higher fibre content will be described since it resulted in stronger material. That is, however, not a universal rule. Some experiments have shown that a higher percentage of fibres can lower the tensile strength since higher fibre fraction introduces more porosity. [21, 22]

Experiment description

In the experiment ABS copolymer was used with 3,2 mm long carbon fibres. [22]

The fibres and the polymer were first compounded and extruded into preforms with 10, 20, 30 and 40 weight %. The printing itself was carried out with a nozzle (0,5 mm diameter) heated to 205°C and the table to 85°C. Layers 0,2 mm thick were layered on each other. The composite was deposited in a direction parallel to the loading direction. The mixture with 40 weight % kept clogging the nozzle and it would therefore be impractical for commercial use. [22]

Testing

The printed composite was cut into dog-bone samples, on which displacement controlled tensile tests were carried out. [22]

Results of the experiment

The specific strength and modulus have both increased in comparison to a samples without the fibres. [22]

It was discovered, that pores formed between the beads on the samples, which happened during printing. The pores, however, run in the main direction of the fibres and loading and should hence have little effect on the overall strength. The experiment uncovered that higher percentage of fibres shrunk the voids thanks to better packing of the mixture. [22]

The ends of carbon fibres, however, cause formation of voids in the beads, leading to a performance decrease. This was blamed on the independent flow of the phases during printing. The formation of voids in beads could be prevented by better attachment of the fibres to the matrix either by using a more compatible combination of fibre and matrix or by coating the fibres in a layer increasing the strength of the bond. [22]

The resulting material had fibres just 0,4 mm long, most likely due to breakage during extrusion compounding and printing with causes similar to those highlighted in chapter 3.1. This should, however, not completely prohibit high-performance applications, provided the fibre aspect ratio is high enough. [22]

The fibres were aligned well, although they were slightly tilted downwards because of the direction of the printing head. No numerical value for how well the fibres were oriented was given. [22]

Figure 31 shows a comparison between samples made from the same preform, one using printing and the other one using compression moulding. The compression moulded sample performs slightly better since it has less voids. The printed sample has, however, better aligned fibres. It can therefore be assumed that if the amount of voids was lowered, the printed sample would outperform the compression moulded one. [22]

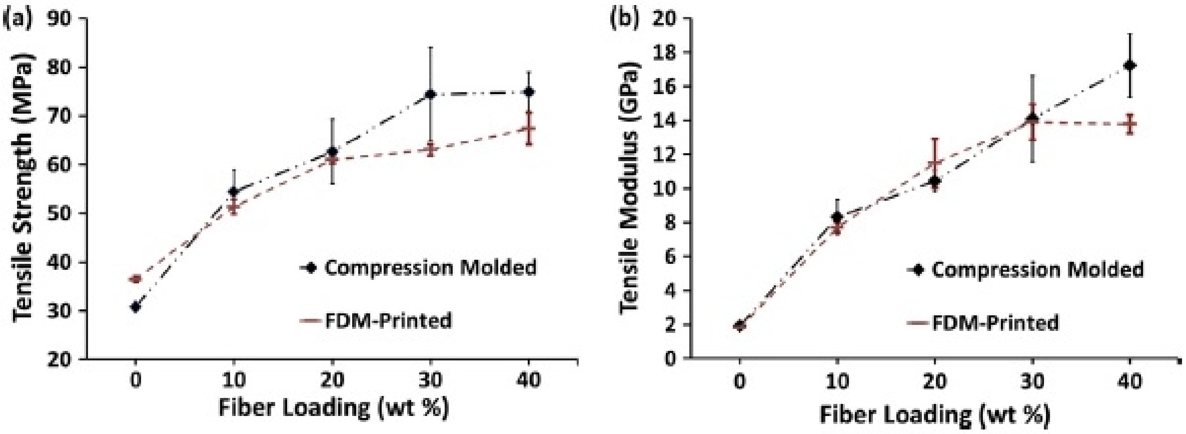


Figure 31: Effect of fibre content and manufacturing process on (a) strength, (b) modulus. FDM – fused deposition modelling [22, pg. 149]

4.9. INDUCED DISCONTINUITY PROCESSES

This group of processes is based on introducing discontinuities into unidirectional long-fibre prepregs. This makes it debatable, whether it is a SFPC method, but for the sake of completeness I have decided to include it. [10]

The reason why the fibres are broken, is almost opposite to all of the other methods. While all the other methods start with an easily formable weak and cheap material, this one begins with a very strong and expensive, but hard to form long fibre composite prepreg, in which the fibres get broken to improve the formability at the cost of a slight deterioration of properties. Figure 32 highlights why this makes sense as there is an optimal point between strength and formability. [10]

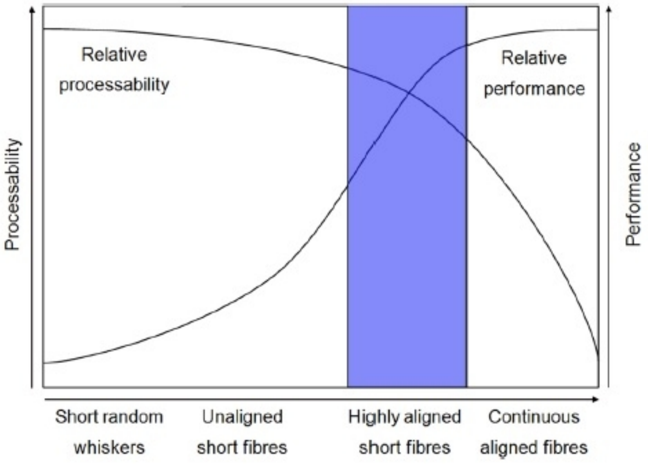


Figure 32: Performance and processability relation, optimum - purple rectangle [10, pg. 164]

Stretch broken carbon fibre

Fibres in the prepreg were initially broken to 100 mm length. In order to make processing easier, this length was later decreased to 50 mm. [10]

Although this method looked very promising according to most reports and the resulting parts exhibited exceptional strength, it is unknown how much or if it is used at all, since it was developed for US department of defence and there seem to be no reports of civilian use. [10]

Perform

Rather than breaking the fibres, this method makes fibres discontinuous by drilling small holes into the prepreg with a laser. [10]

This method has also achieved exceptional results but it is very rarely used. [10]

5. PROPOSAL OF A NEW METHOD FOR ALIGNING SHORT FIBRES

5.1. ELECTRIC CURRENT METHOD

Although electric field has been used for aligning fibres, the use of electric current has not been experimented with or even mentioned in any of the articles and books.

The idea behind the method

As electric current flows through a conductor, magnetic field is generated around it, which can generate magnetic forces. If electric current was to flow through the matrix and the fibres, each fibre would generate its magnetic field which would interact with the fields of the other fibres. This interaction would exert magnetic forces on the fibres, which could orient them in the direction of the flow of electrons.

Problems & obstacles

There are several obstacles. Firstly this method would only work with conductive materials. That is not a major problem for fibres, as one of the most commonly used fibre types is carbon fibre, which is highly conductive, but it is an issue for polymers. The polymers that are used for conventional manufacturing methods are not electrically conductive. This can be helped by the addition of electrically conductive fillers. This does, however, lead to a decrease of strength and in some cases thermal instability.

There are conductive polymers available, such as polyacetylene, PPV, PPY, polyanilines, PT or PPS but they are not commonly used for manufacturing of high-performance composites, therefore there is little to no information regarding their use in such a way. The only one, which has been mentioned in literature is polyphenylene sulfide (PPS), which is used in additive manufacturing. [23] There is also a patent for composite with polyacetylene matrix but I could not find any further references of this composite being used. [24]

The bigger problem is the unpredictability of the flow of the current through the part with fibres. Since the fibres would be more conductive than the matrix, the current would no longer flow as shown in figure 33a but rather choose the randomly dispersed fibres. This would lead to unpredictable magnetic field interactions. Furthermore, if the viscosity of the liquid was low enough all of the fibres would move to the middle and form one conductive fibre, since the force acting on conductors when the current flows through them in the same direction, moves them together. This could be influenced with the viscosity of the matrix since the magnetic force decreases when the fibres get closer, so that at certain distance the viscous forces would get higher than magnetic ones.

Possible advantages

If the fibres aligned themselves in the direction of the flow of electrons in a material without fibres, it could be very beneficial to the mechanical properties of parts with complex shapes and stress concentrators. The flow of electrons in a material without fibres is going to be the same as the direction of stress around various shapes, ergo if the fibres got aligned in the same direction the composite would have the fibres aligned in every place in the stress direction. The electric current distribution in a fibreless part was verified in ANSYS workbench as seen in figure 34. An example with a plate with a hole can be seen in figure 33. Figure 33a shows the stress concentration in the part, which matches the flow of the electric current. Figure 33b shows fibres aligned by a homogenous field or by some other method used for creating aligned fibre preforms with the hole drilled after manufacturing. Figure 33c shows the fibre distribution if electric current was used for alignment and the fibres aligned as intended and it highlights that the fibres are aligned perfectly parallel to stress in every point.

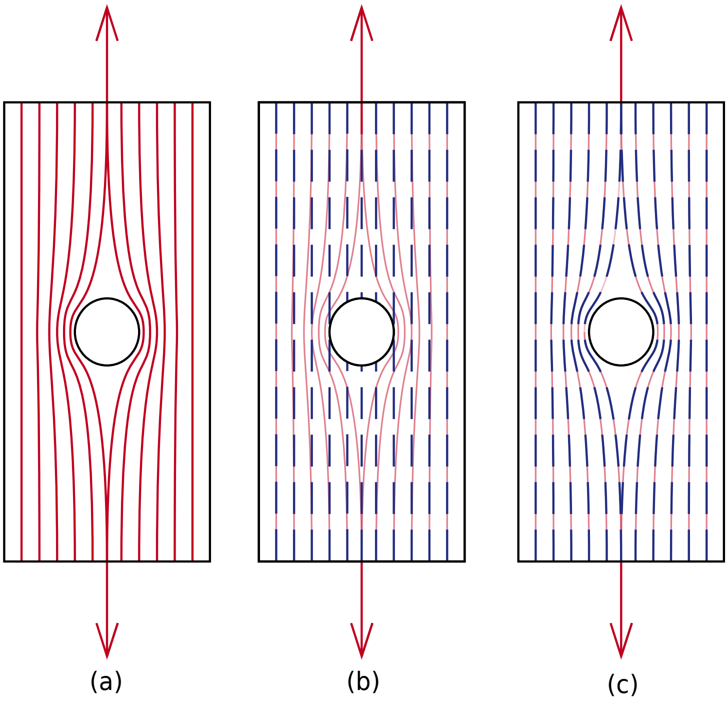


Figure 33: Plate stressed in vertical axis. (a) stress in the part/flow of electric current, (b) fibres aligned by a method with homogenous field/from aligned fibre preform (c) distribution of fibres in a part made using electric current flow

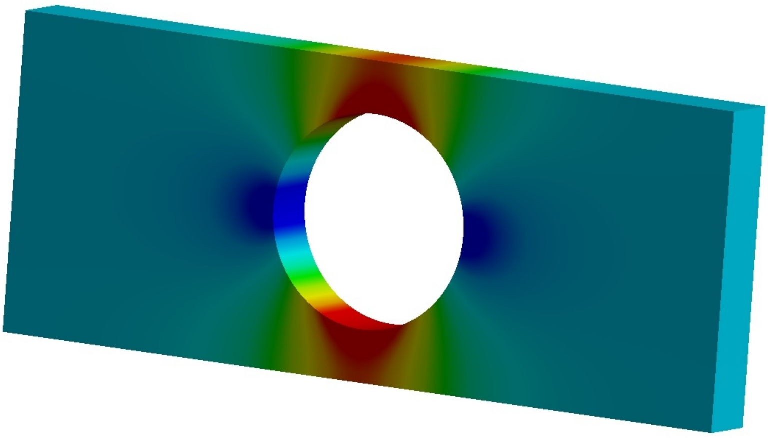


Figure 34: Total current density in a plate with a hole displayed in ANSYS Workbench

5.2. ALTERNATING MAGNETIC FIELD METHOD

The idea

When a conductor is placed into changing magnetic field, voltage and eddy currents get induced in the volume of the conductor. According to Lenz's law the currents flow in such directions that the field they generate opposes the field change that induced the current. The conductor will behave like a magnet, whose magnetic moment will experience torque if it is not aligned with the magnetic field. This phenomenon might cause alignment of conducting non-ferromagnetic fibres in a non-conducting matrix or water.

Problems & obstacles

I was not able to determine what field change ($\mathrm{d}B/\mathrm{d}t$) would be necessary to cause fibre alignment in one time-interval of monotonic field increase. Alternating field or similar periodically oscillating field may appear as a way to prolonging the aligning effect, but the quarter-period time shift would result in alternating polarity of the torque, and hence zero net effect.

Another unknown in this process would be the redistribution of currents in the fibres due to the reorientation, related to the total energy of the fibre in the imposed magnetic field. The process might also involve the fibre and matrix transport, and changes of its fluidity. A complex physics simulation including Maxwell's equations along with object mechanics in a viscous fluid, fluid dynamics and, in some cases, also heat transfer would be required. Such analysis was, unfortunately, beyond the scope of this work.

Advantages

If a functioning process scheme was found, it would be an advantage that the fibre and matrix materials would be less restricted than in methods utilizing matrix conductivity or fibre ferromagnetism.

6. SUMMARY

The objectives of this thesis were to describe, analyse and summarize manufacturing methods of SFPC, to describe and analyse the methods for improving the mechanical properties of SFPC and to propose a new method.

Based on the review of literature, the methods were described along with the advantages and disadvantages and at the end compared in a chart. Compression moulding is the most universal method thanks to the wide variety of usable compounds and prepregs/preforms with aligned short fibres. Spray-up, on the other hand, is a much cheaper and simpler method offering unique options such as on-site manufacturing but with the downside of a lower volume fraction, thus limiting the maximum strength. Injection moulding is a fast and wide spread method for manufacturing polymer parts and the tools require little changes to accommodate manufacturing of composites. Last but not least, additive manufacturing is seeing a rapid development and has a great potential, although its use for composite manufacturing is in its infancy.

Methods for improving properties of short fibre composites are almost as old as composites. They have, however, seen a rise of interest in the past three decades because of the renewed interest in composites that are cheaper than the long-fibre ones while having only marginally worse mechanical properties. First methods to be developed were hydrodynamic methods, which used viscous liquids. Their use complicated the manufacturing process and made it longer. Then came pneumatic methods, which were faster, but could not match the accuracy of fibre alignment of the hydrodynamic methods. New progressive approaches appeared, such as electrical, magnetic and ultrasonic ones but they all suffer from having low volume fraction, insufficient fibre orientation or the combination of both. There was also a method to help align fibres during injection moulding but it never caught on commercially. A new promising high-performance method – HiPerDiF was developed in 2014. HiPerDiF is a hydrodynamic method but unlike the other ones it uses water, which is much less viscous than liquids used with other hydrodynamic methods. That massively boosts the speed and efficiency of the alignment process. Furthermore HiPerDiF is designed in a way that allows high-volume production of prepregs with vastly superior mechanical properties in comparison to all other methods. Last but not least, additive manufacturing is also well suited for fibre alignment, but similar to regular 3D printing of composites, the technology is still developing and is not yet mature enough for mass commercial use.

Finally two new methods were suggested. First method would use electrically conductive fibres and matrix and the alignment would be induced by the interaction of the magnetic fields generated by the current flowing through the fibres. There are, however, nowadays no conductive polymers that are commonly used for manufacturing composites. If this method were to work as intended it would allow for fibres to be aligned around a variety of shapes and the fibres would therefore transfer and absorb the stresses better, thus improving the strength and modulus even further than simple unidirectional alignment.

The second method uses an alternating magnetic field, which induces eddy currents and an opposing magnetic field that might align the fibre, although more research regarding this method is required.

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