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Guidebook for Manufaturing CFRP Parts

Automotive Exterior Parts

Helsinki Metropolia University of Applied Sciences

Bachelor of Engineering

Automotive and Transport Engineering

Bachelors Thesis

Date 3. September 2012

Helsinki Metropolia University of Applied Sciences

Preface

This bachelor's thesis is part of my Bachelor of Engineering studies at the Automotive Engineering Department in Helsinki Metropolia University of Applied Sciences.

The study was requested by Valmet-Automotive Ltd. to increase their knowledge in the field of carbon fibre reinforced plastics manufacturing. The aim of the study was to provide the company a guidebook that could be used by their different departments.

As a newcomer in the field of this study it has been challenging and educative for me to write the thesis. I wish to thank that my supervisor and instructor as well as my language instructor for the guidance and help they have given me in order to complete my thesis in the given time frame and in such a pleasant way. Especially the employees at Valmet-Automotive Ltd. have been very supportive and easy to work with.

Finally I want to express my gratitude to my girlfriend for supporting me during my Bachelor of Engineering studies.

Uusikaupunki, 3. September 2012

Tuomas Kaila

Author(s) Title Number of Pages Date	Tuomas Kaila Guidebook for Manufaturing CFRP Parts 69 pages + 6 appendices 3. September 2012
Degree	Bachelor of Engineering
Degree Programme	Automotive and Transport Engineering
Specialisation option	Automotive Design
Instructor(s)	Jari-Petri Siirilä, Manager, Prototypes, Valmet-Automotive Inc. Harri Santamala, Project Manager, Helsinki Metropolia University of Applied Sciences

This Bachelors Thesis was carried out for Valmet-Automotive Ltd. which is a leading service provider in automotive industry. Since there is a growing demand for automobiles that consume less energy whilst retaining the crash safety and structural attributes of conventional automobiles, the carbon fibre composites might prove suitable as a replacing material for metallic counterparts due to their light weight and high strength.

The aim of this Thesis was to produce a guidebook for the company to provide basic information on the materials, equipment and manufacturing of carbon fibre composite parts used in exterior applications. The resulting guidebook was designed so that it could be used by different departments of Valmet-Automotive Ltd. in fields of engineering, purchase, logistics and paint shop etc.

This Thesis resulted in a guidebook that provides basic information on CFRP materials and manufacturing techniques used in automotive exterior applications whilst improving the knowledge of the company’s own capabilities in the aforementioned field. Also occupational health and environmental concerns such as recycling were incorporated in the guidebook.

Keywords	Carbon fibre, Composites, CFRP

Tekijä(t) Otsikko Sivumäärä Aika	Tuomas Kaila Guidebook for Manufaturing CFRP Parts 69 sivua + 6 liitettä 03.09.2012
Tutkinto	Insinööri AMK
Koulutusohjelma	Auto- ja kuljetustekniikka
Suuntautumisvaihtoehto	Tuotetekniikka
Ohjaaja(t)	Jari-Petri Siirilä, Manager, Prototypes, Valmet-Automotive Oy Harri Santamala, Projekti-insinööri, Metropolia Ammatikorkeakoulu

Tämä opinnäytetyö toteutettiin Valmet-Automotive Oy:lle, joka on autoteollisuuden johtava palveluntarjoaja. Vähän energiaa kuluttaville ja samalla turvallisille ja rakenteellisesti kestäville autoille on kasvava kysyntä. Tästä johtuen hiilikuitukomposiitit saattavat olla hyvä vaihtoehto korvaavaksi materiaaliksi perinteisille metalleille, koska ne ovat kevyitä ja kestäviä.

Opinnäytetyön tavoitteena oli tuottaa yritykselle käsikirja, jossa on perustietoja autojen ulkopaneeliosissa käytettävien hiilikuitukomposiittien materiaaleista, valmistuksesta ja valmistuksessa tarvittavista laitteista ja apuvälineistä. Lopullinen käsikirja suunniteltiin siten, että Valmet-Automotive Oy:n eri osastot, kuten esimerkiksi suunnittelu-, hankinta-, logistiikkaosasto ja maalaamo voisivat hyödyntää sitä.

Opinnäytetyön tuloksena on käsikirja, joka sisältää perustietoja autojen ulkopaneeleissa käytettävien hiilikuitukomposiittien materiaaleista ja valmistustekniikasta. Samalla yrityksen tietämystä omista kyvyistään edellämainitulla aihealueella kasvatettiin. Käsikirjaan sisällytettiin myös terveys- ja ympäristö asioita, kuten kierrätystä.

Avainsanat	Hiilikuitu, komposiitit

Contents

Vocabulary and Acronyms

Accelerant	Accelerates the curing of the resin
BMC	Bulk Moulding Compound
CFRP	Carbon Fibre Reinforced Plastics
CoC	Certificate of Conformity
CS	Chopped Strand
CSM	Chopped-Strand Mat
CTE	Coefficient of Thermal Expansion
Debulk	To remove air out of the laminate
DLF	Degraded Laminate Failure
FRP	Fibre Reinforced Plastic
HDT	Heat Distortion Temperature
ILS	Interlaminar Shear
ILSS	Interlaminar Shear Strength
IM	Injection Moulding
LFI	Liquid Film Infusion
MF	Milled Fibre
NDI	Non-destructive Inspection
NDT	Non-destructive Testing
OEM	Original Equipment Manufacturer
RIM	Reaction Injection Moulding
RRIM	Reinforced Reaction Injection Moulding
SRIM	Structural Reaction Injection Moulding
RT, RTA	Room Temperature Ambient
RTC	Reinforced Thermoplastic Composite
RTM	Resin Transfer Moulding
SMC	Sheet Moulding Compound
SPEC	Specification
TMA	Thermal Mechanical Analysis
UD	Unidirectional
VARTM	Vacuum Assisted Resin Transfer Moulding
VI	Vacuum Infusion / Injection
VIP	Vacuum Infusion / Injection Process

1 Introduction

The automotive industry is requesting advancement in material technology due to the tightening of the CO_2-restricting legislation and as well to improve the operational range of electric vehicles. In order to meet the requirements the cars have to be made of lighter materials that at the same time provide the same crash safety features as conventional ones and this is why carbon fibre reinforced plastics (CFRP) are seen as one possible solution. CFRP is claimed to have higher weight specific strength than steel or aluminium.

Valmet-Automotive is a leading service provider for the automotive industry in fields of automotive engineering, vehicle manufacturing, convertible roof systems and related business services. The areas of their expertise are premium cars, convertibles and electric vehicles. To be able to help their customers to succeed in making vehicles lighter and more efficient having a good knowledge of CFRP manufacturing provides a great advantage.

In this thesis the emphasis is on the exterior parts that also have to stand external loads though the loads are different than in structural parts. The resulting guidebook provides basic information on the composites and their manufacturing processes together with safety and environmental matters. It is designed to give basic guidelines for whoever is about to consider purchasing or manufacturing exterior parts made of CFRP.

The guidebook starts from composite materials such as resins and reinforcements and their characteristics. The composite materials section also contains information of storing and some examples of suppliers. Common equipment for mould making, curing and tooling can also be found in this guidebook together with the related process parameters. Manufacturing techniques mentioned in this guidebook are chosen according to their suitability to produce exterior parts for cars whereas a comparison of techniques can also be found. Refining and quality matters are incorporated in this guidebook as well along with safety and environmental concerns.

2 Composites

Composite material consists of at least two different substances that do not dissolve in one another. In this thesis the focus is on CFRP which consist of carbon fibres that can be continuous, chopped or milled and a plastic matrix. Fillers and additives with different purposes are normally also used. Materials used in composites are not as durable separately as they are when combined to a composite structure [2, p 221].

The fibres carry the external loads and the plastic matrix connects the fibres to one another transferring loads from one fibre to another and also acts as the visible surface of the part. Fillers and additives are mostly used for making the parts cheaper though depending on the types used they can also provide some other functions e.g. chemical or heat resistance etc.

2.1 Characteristics

Every plastic and reinforcement has its own characteristic attributes when it comes to surface quality, appearance and structural features. The plastics differ from each other as well in hygroscopic and thermal attributes.

2.1.1 Hygroscopic and Thermal Attributes

Some of the plastics used in CFRP parts tend to absorb moisture. Moisture in the parts can cause them to lack desired structural qualities and to cause surface defects and therefore controlled working conditions are important. Average mass gain for a composite part when conditioned can be seen in Figure 1.

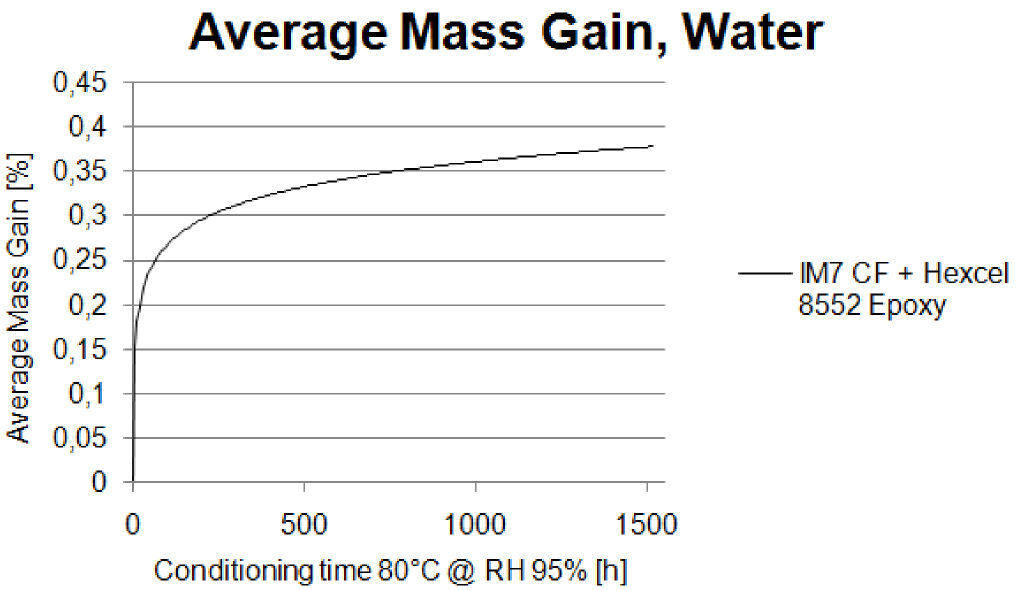
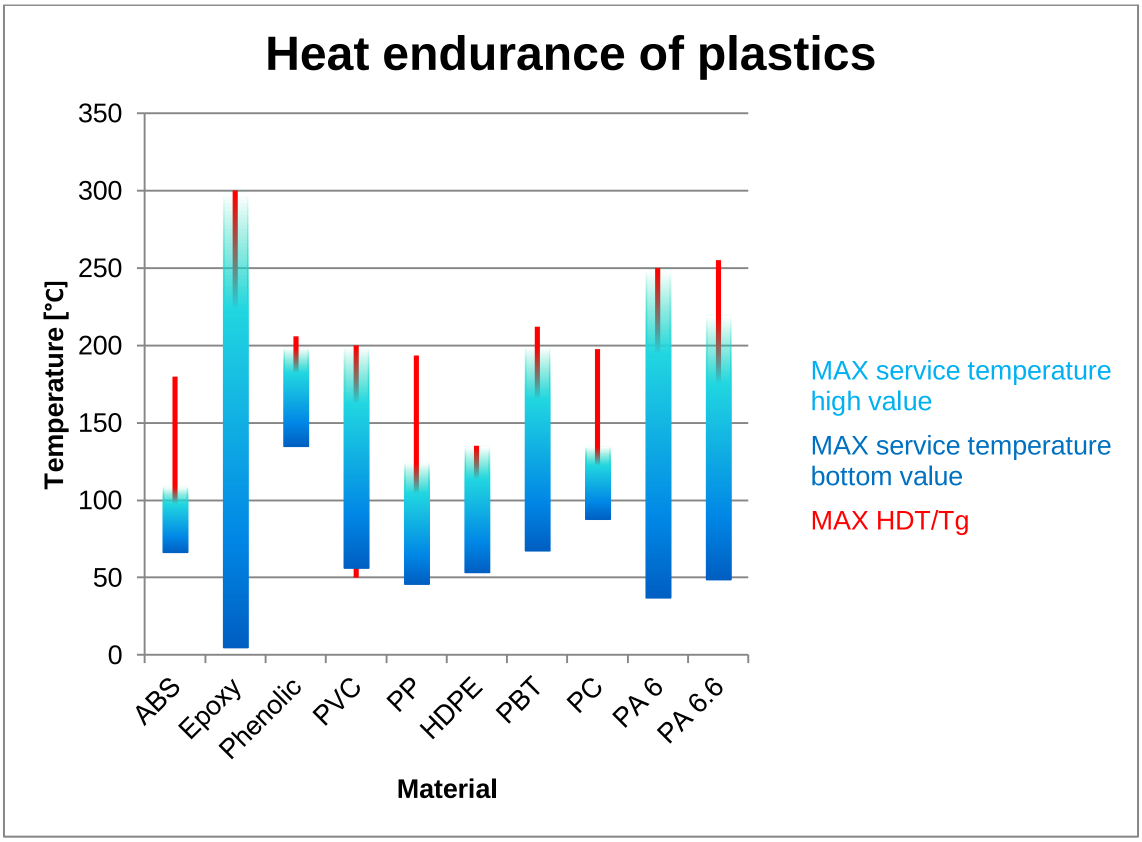


Figure 1. Average mass gain of composite when it has been conditioned [16].

As seen in Figure 1 a CFRP part can absorb nearly 0,4 wt% of moisture after 1500 hours of conditioning.

The heat endurance of the plastic matrix is usually significantly lower than in the metallic parts therefore when the CFRP parts are heated during the paint curing process deformations may appear. These deformations may occur because of release of the internal tensions of the part or just because the part has softened.

The HDT and T_g figures represent the maximum heat endurance limit for different plastics. For thermoplastics the heat distortion temperature (HDT) value defines the temperature at which a plastic part deflects under specific load. The test procedure is described in standards ASTM D648 and ISO 75. When using thermosetting plastics, glass transition temperature (T_g) applies and the corresponding test procedure is described in ASTM D7028 and ISO 6721-11 [1, p 292]. There is also a maximum service temperature defined for plastics. A comparison of heat endurance and maximum service temperature between different plastics can be seen in Figure 2.



Picture 2. Heat endurance of different plastics.

As seen in Figure 2 the heat endurance of different plastics can vary among a single type of plastic.

In addition the coefficient of thermal expansion (CTE) of plastics differs from metallic counterparts. When a plastic part is attached to the BIW and then heated during the painting process, it may deform or cause other problems if it is not attached in a flexible way. A chart of CTEs of different plastics can be seen in Figure 3.

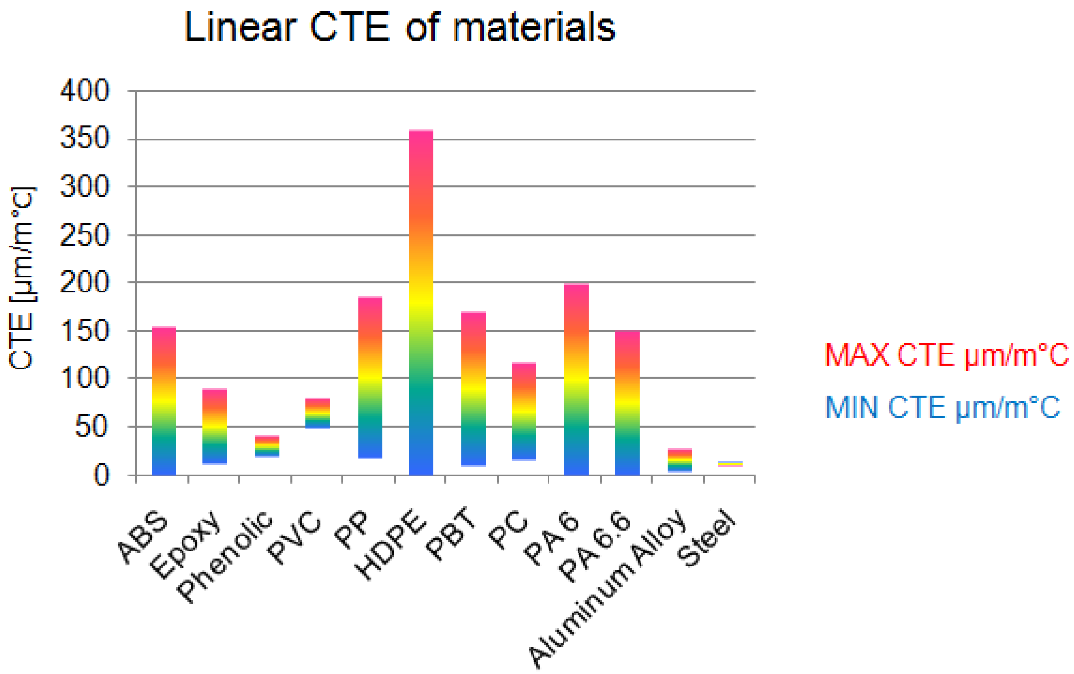


Figure 3. The Linear CTE of common plastics, aluminium alloy and steel [14].

As seen in Figure 3, there is a great amount of variation in the CTE even among a single type of plastic. It means that with a correct mix of ingredients, additives and fillers the CTE can be brought to a suitable level for each application. The reinforcements usually have smaller CTE than the matrix plastic, sometimes even negative, and can thus cause read-through effect on the parts surface after heating in the painting process.

2.1.2 Mechanical Short Term Attributes

The main difference between metals and composites is that metals are homogenous and isotropic whereas composites are orthotropic and heterogeneous. Metals have the same mechanical attributes in every direction but the composites have different attributes in every three dimensions. Most of the composite structures are, or consist of, thin layers and therefore it is essential to examine the attributes of a thin laminate structure [21, p 383]. The laminate axis system and angles are described in Figure 4.

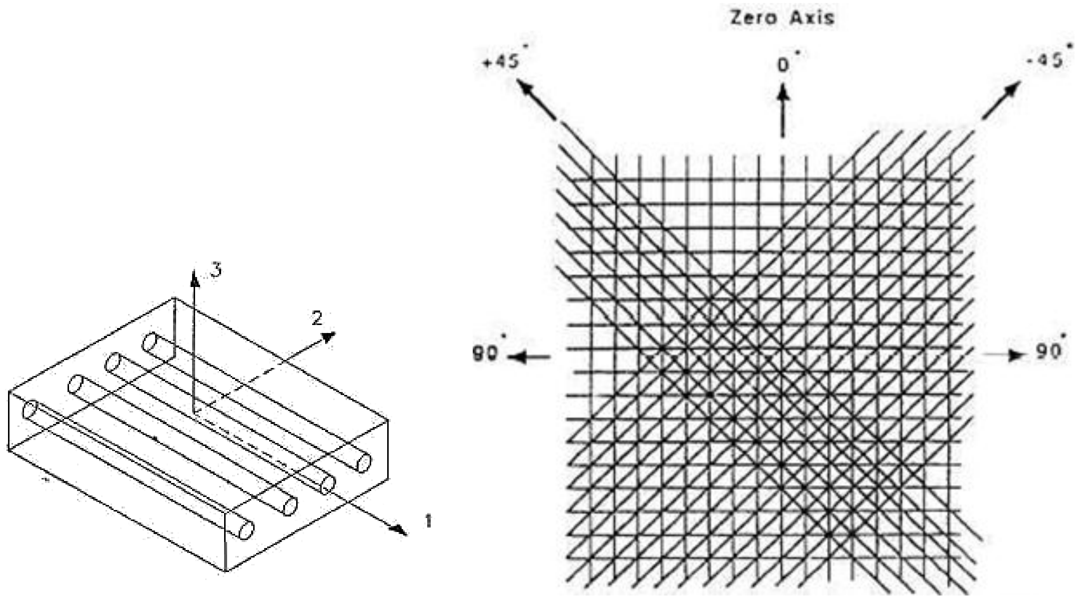


Figure 4. Laminate axis system [13].

The axis system seen in Figure 4 is also often referred as x, y and z in the same corresponding order 1, 2 and 3. Zero axis is defined by the main assembly direction.

The requirements for parts whether they are surface or structural parts are different. For characteristics and loading, a comparison for part types can be seen in Table 1.

	Surface part		Structural part
Part type		Shell structure with double curvature Hollow profile with var. cross section	Compact part with complex load paths
Load type		Cyclic loads Crash loads	Permanent loads
Surface	Class A	“Effect” surface	Technical surface
Requirement	-40°C to 105°C (plus paint curing)	Min/max strength	-40°C to 80°C (plus paint curing) Constant stiffness

Table 1. Characteristics and loading of FRP parts [18, p 62].

As seen in Table 1, the requirements for different part types can be challenging since for example the surface parts have to endure a wide range of temperatures whilst maintaining the class A surface quality and fatigue stress behaviour. On the other hand the structural parts will need to incorporate complex load paths in some applications that in turn requires highly precise placement of reinforcements.

In a structural point of view it is essential for the exterior parts to have good fracture behaviour, impact strength and good load bearing abilities perpendicular to the surface since the type of parts mentioned are not part of the BIW structure. Internal rigidity is also a factor that should be noted and this so called buckling behaviour can be controlled by shaping the part correctly but also with the placement and direction of the reinforcements [18, p 31 and 34]. The international standard ISO 179 defines the ways of testing impact strength of a plastic part. The determination of flexural properties can be found in ISO 178 and for tensile properties testing, the standard ISO 527 applies.

2.1.3 Deformations during Manufacturing

Thermosetting plastics tend to shrink during the curing process. The shrinkage has its effects on the part to be made though reinforcements usually have a tendency to prevent it. The overall shrinkage and deformation result from the orientation of reinforcements as well as from the resins composition and the fillers' behaviour when heated [1, p 234]. The dimensional alteration of composite parts along x-axis after heating and cooling cycles can be calculated with the following formula:

$$\Delta L_x = L_x[\alpha_x(T_{ref} - T_c) - S_x],$$

in which the ΔL_x is the length alteration along x-axis, L_x is the starting length, α_x is the linear CTE of the cured part, T_{ref} is the reference temperature, T_c is temperature in which the resin is fully cured and S_x is the composites cure shrinkage along the given direction. In addition to shrinkage along a certain direction, the material shrinkage can cause deformations to the part which is especially the case when an asymmetric laminate is being used. Therefore it is advisable to use symmetric laminates if possible. An example of deformation in a corner can be seen in Figure 5.

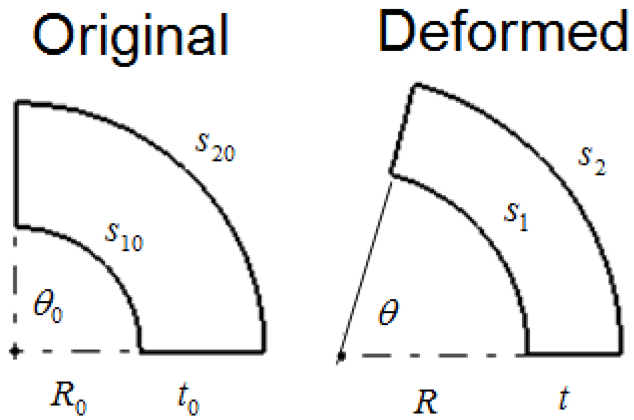


Figure 5. Deformation in a parts corner [1, p 234].

In Figure 5, the R is the inner radius of the corner, t is the thickness, s stands for the length of the surface and θ is the circumferential angle of the corner. It can be seen that all of the figures tend to change and thus cause deformations in the part.

The overall deformation results from adding up directional thermal expansion attributes, cure shrinkage and internal tensions caused by the curing process. As for a symmetric laminate, following formula can be used for calculation of the overall angle deviation in a corner:

$$\Delta\theta = \Delta\theta_T + \Delta\theta_S + \Delta\theta_C,$$

in which $\Delta\theta$ stands for overall angle deviation, T is for thermal expansion, S is for cure shrinkage and C stands for angle deviation caused by internal tensions [1, p 234].

Most of the angle deviation is caused by directional thermal expansion, since FRP parts are not homogenous. They tend to expand less in the direction of the fibres (α_x), than in the perpendicular (z α_z) direction. If the laminate is presumed to be homogenous, the angular deviation in a corner caused by temperature change ΔT can be calculated with the following equation:

$$\Delta\theta_T = \frac{\theta_0(\alpha_x - \alpha_z)\Delta T}{1 + \alpha_z \Delta T},$$

in which the θ_0 is the original value of the angle, α_x is the thermal expansion along x-axis and α_z is the thermal expansion along z-axis. For a CFRP part the deviation of a 90°-angled corner is approximately $\Delta\theta_T = -0{,}004°/°C$ [1, p 234].

The best way to determine the angle deviation is sample testing, since the $\Delta\theta_S$ and $\Delta\theta_C$ are difficult to calculate because the part is normally heterogeneous in the corners which in turn is caused by the fibres tendency to pack in the inner side of the corner. The deviation of the corner radius is due to perpendicular thermal expansion caused by temperature change and can be calculated from following equation [1, p 234]:

$$\Delta R = R_0 \alpha_z \Delta T \,,$$

in which ΔR is the overall corner radius deviation, R_0 is the original radius, α_z is the thermal expansion along z-axis and ΔT is the temperature change.

2.2 Materials

It is essential that the compatibility of the reinforcing fibres and the plastic matrix is checked otherwise the plastic matrix will not adhere to the fibres. The reinforcements can be fabrics composed of chopped, milled or continuous fibres that can be in unidirectional from or in two or more directions in woven or non-woven fabrics. There can also be a combination of reinforcements of different materials used. The fabrics are provided with coatings of different functions which include binders that help to keep the fibres attached to one another and tackifiers that are used to improve adhesion between matrix plastic and the reinforcements. The most typical Tackifiers are silane-based though the right kind should be chosen according the suitability for matrix plastic used.

2.2.1 Resins and Plastics

The desirable attributes for matrix plastics are good mechanical features e.g. compression strength, tendency of internal fractures, delamination and fracture build-up behaviour. The viscosity of the resin should be suitable for the chosen manufacturing technique as for example in injection techniques the viscosity should by higher than in the hand lay-up. The resin should have appropriate gel-time according to the chosen technique and also good heat and chemical resistance are normally requested.

In present day the cost of the material and its application are the base for deciding the right combination. The most commonly used resins in CFRP parts and their usual applications as well as some other characteristics can be seen in Table 2.

	Resin	**Application & Characteristics**
Thermosetting plastic	Epoxies	• the most used plastic matrix in aircraft industry • good mechanical features, chemical and heat resistance, minor mould shrinkage
	Vinyl esters	• used in wind power, sea vessel, process and chemical industry • good heat and chemical resistance
	Polyesters	• commonly used in sea vessels • cheap and easy to manufacture
	Urethanes	• new short cycle-time resins • developed for automotive applications among others
	BMI (Bismaleimide)	• rigid and thermally stable approx. 250°C, good mechanical attributes • one-component, can be cured just by heat
Thermoplastic	PEEK (Polyether ether ketone)	• commonly used in air- and spacecraft industry • excellent heat and environmental endurance
	PEI (Polyether imide)	• growing market in aircraft industry • flame retardant
	PPS (Polyphenylene sulphide)	• suitable for dimensionally accurate parts • good mechanical qualities, excellent heat resistance

Table 2. Common resins and their applications [13].

It can be seen in Table 2 that the majority of plastics used in CFRP applications are still thermosetting plastics though they lack the recyclability and reusability that of thermoplastics whereas they provide with more desirable attributes relative to cost.

2.2.2 Resin Mix-in Additives

Resin mix-in additives are used for cost reduction purposes as well as to provide additional aspects. The additives can provide the material with flame retardance, UV-protection or reduce friction. They can also be used to control the thixotropy of the resin in other words to prevent the resin from flowing on vertical surfaces.

The most desirable type of filler would be a soft surfaced sphere since it has minimum effect on the resins viscosity and in damaging the infusion equipment. In addition, it would not cause internal tensions to the matrix plastic [1, p 58]. For example hollow spheres are used to make parts lighter whilst sphere-shaped fillers also make the plastic easier to grind. Common shapes of resin mix-in additive particles can be found in Table 3.

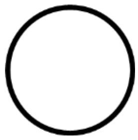
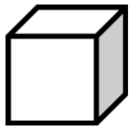
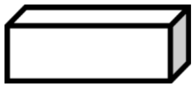
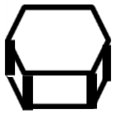
Shape	Ball	Cube	Block	Flake	Fibber
					
Ideal Shape	Ball	Cube, rhombo-hedral	Prism, flat, pinakoid	Flake, plate, slate	Fibber, needle-like
Aspect ratio: -Length (L) -Width (W) -Thickness (T)	 1 1 1	 1 1 1	 1,4-4 1 1-<1	 1 <1 1/4-1/100	 1 <1/10 <1/10
Examples	Micro spheres, balls	Calcspar ($CaCO_3$), feldspar, heavy spar, silicon dioxide		Kaoline, talc, crystals, mica	Wollastonite, natural fibres

Table 3. Common shapes of filler particles [1, p 60].

As seen in Table 3 there is a good variety of different shapes of fillers for different applications and the rarest being the needle like mineral fillers.

Calcium carbonate ($CaCO_3$) is the most common type of filler. Approximately half of the amount of fillers used is calcium carbonate filler since it can be used to control resin viscosity, improve surface quality and prevent mould shrinkage. It is cheap and always available in a large variety of particle sizes such as dry and wet grinded types, purified or precipitated grade are available in various coatings and finishes. Calcium carbonate can endure temperatures up to 600°C [1, p 61 and 62].

Magnesium carbonate ($MgCO_3$) is used in lay-up resins and cast resins. It can be used as common filler or with antimony trioxide to improve flame resistance attributes [1, p 62].

A common form of calcium silica ($CaSiO_3$) is wollastonite. It is the only mineral filler which has a fibre-like particle shape and it is mainly used as filler in thermoplastics and it can also come in finished forms. Calcium silica has minimal moisture absorption features and because of its particle type, it can be used for reinforcing to some extent [1, p 62].

Kaoline ($Al_2O_3 \cdot 2SiO_3 \cdot 2H_2O$) in natural form includes crystallised water and can be used as it is or in calcinated form that excludes water and is harder than the natural form. Kaoline is used in reinforced plastics to hide the reinforcing fibres and to improve surface quality and prevent hairline cracks, mainly in SMC and BMC. It can be used to decrease electrical conductivity. When used with epoxy or vinyl esther resins, it has to be coated since it is acidic. Kaoline has good acid and alkali resistance [1, p 62].

Mica can be found in boulder form and sliced into small flexible plate-shaped particles that can be used as fillers. There are several types of micas of which the most common are muscovite, phlogopite (amber mica), biotite (black mica) and lepidolite (lithia mica). Mica can be found as wet or dry grinded types with different finishes and depending on the chemical purity they can come in various colours. With suitable aspect ratio and reduced amount of porosity mica can be used to make a plastic that has the tensile modulus of aluminium and tensile strength of 200 - 300 MPa. Mica can also be used to improve electrical conductivity, dimensional stability and heat, weather-, corrosion and moisture resistance as well as chemical resistance and prevent mould shrinkage and reduce CTE. They can have negative effects on the composites strength attributes and they can be used together with micro spheres for better packing density and resin flow [1, p 63].

Feldspar is suitable for usage in SMC and BMC, especially with PVC and it can be used in high percentage in particular when used together with other more fine-grained fillers. Feldspar can prevent shrinkage, increase stiffness and improve weather, abrasion and chemical resistance. It has a positive effect on resin flow and cast behaviour as well as on reducing the need of pigment usage [1, p 63].

Zirconium silica ($ZrSiO_4$) can be used to prevent electrical conductivity, improve heat resistance, significantly decrease humidity absorption, and mould shrinkage. If used with polyester resin, it can be used to accelerate the curing process. It can also be used as pigment [1, p 63].

Talc can appear in plate-, fibre-, needle-like or indefinite boulder form and in its purest form it is the softest known mineral. It has a cost reducing effect since it is a cheap substance. The usual shape used in plastic industry is plate-like and therefore it has a reinforcing effect on matrix plastics. With plate-like talc, higher stiffness and creep resistance are gained in high temperatures than with any other filler with the same percentage used although it reduces impact resistance. Talc is not electrically conductive and has reduced thermal conductivity. It has also a reducing effect on polyester resins peak exotherm but on the other hand it increases the viscosity of resin even in small quantities [1, p 63].

As a resin mix-in additive aluminium oxide (Al_2O_3) improves electrical resistivity, heat conductivity, hardness and wear resistance. It is highly resistant to chemicals and has a low CTE and it can also be used in polyester and epoxy resins for slip prevention purposes [1, p 64].

Silica (quartz) is the most common of silicon chemical compounds. Its hardness has an abrasive effect on the tools used especially with thermoplastics though when used with thermosetting resins it improves electrical resistivity, dimensional stability and thermal conductivity. It has a very low CTE. Pyrogenic silica is the most common type of silicon compound used in thermosetting plastics and its particles are sphere-shaped whilst they have a strong effect on thickening and thixotropy. The effect on thixotropy is the reason why Pyrogenic silica is used with polyester, vinyl ester and epoxy to prevent them from flowing on steep angled or vertical surfaces. The negative side is that it causes resin-rich and resin-starved areas to appear on the part [1, p 64]. Common types of mineral fillers and their characteristics can be found in Table 4.

Filler	Density [g/cm³]	Hardness [Mohs]	Particle size [µm]	Colour	Particle shape
Calcium carbonate					
-calcspar, drygr	2,7-2,8	2,5-3	5-75	white	cube, boul-
-calcspar wetgr	2,7-2,8	2,5-3	0,5-15	white	der
-precipitated	2,6-2,7	2,5-3	0,05-2	white	
Magnesium carbonate	2,8-2,7	3,0-4,5	0,5-15	white	
Calcium silicate					
-Wollastonite	2,9-3,0	4,5-5	0,5-30	white	fibre-like
Kaoline	2,5-2,7	2-2,5	0,3-10	white, light brown	cube, boul-der
Mica	2,7-3,4	2,5-3	1-14	coloured	plate
Feldspar	2,6	5,5-6,5	0,3-90	white, trans-parent	cube, boul-der
Talc	2,4-3,0	1-2	0,05-60	white	flake, boul-
Silica (quartz)	2,6-2,7	6,5-7	0,5-40	gray	der
Pyrogenic silica	2,1-2,2	5	0,007-0,016	white	sphere-like
Antimony trioxide	5,2-5,7		0,8-2,5	white	fibre-like
Aluminium hydroxide	2,4	2,5-3,5	0,05-150	white	boulder
Microspheres					
-solid (glass)	2,4-2,5	5,5	5-800	colourless	sphere
-shallow (lime ash)	0,3-0,85	5	5-300	gray	sphere
-shallow (synthetic)	0,21		10-180	white	sphere

Table 4. Common fillers and their characteristics [1, p 68-69].

It can be seen in Table 4 that the most common densities of fillers are below 3 g/cm³ and can be as low as 0,21 g/cm³ in case of synthetic microspheres. The hardness varies from 1 – 7 in Mohs scale and the particle sizes vary widely from 0,007 – 800 µm.

There are also several other types of fillers used that can be other minerals, glass in various forms, metallic and organic fillers as well. Metallic fillers are mainly used for decoration purposes but also sometimes for altering the attributes of the material. They provide the plastic with electrical and electromagnetic features and with friction reduction or radiation protection [1, p 65-66].

Carbon black can be used to improve workability, electrical conductivity and to add UV- and thermal radiation protection and it comes in different shapes and sizes. With graphite powder it is possible to make a plastic part self lubricating though in great percentages graphite can reduce mould shrinkage. When combined with mineral fillers, it is possible to make thermoplastic parts with tight dimensional tolerances [1, p 66].

Organic fillers can be anything from wood flour to hemp and other fibres gained from plants. They can also be used as reinforcement and weight reduction though the negative side is that the quality of the organic fillers isn´t stable, they tend to absorb moisture and are susceptible to fungus and insect attacks. Organic fibres have the ability to provide the plastics with environmental friendliness which also makes the plastic easier to recycle [1, p 66]. An automotive application can be seen in Figure 6.

Figure 6. Lotus Eco Elise with organic hemp fibre composite [17].

As seen in Figure 6 the organic fibres, in this case hemp, also provide the part also with certain appearance if desired.

Although some plastics are naturally flame retardant, in many occasions specific fillers are used to prevent flammability and to control burn behaviour. Normally these functions are gained by mixing chlorine-, bromine- or phosphor-including compounds with the resin. To reduce smoke formation, different zinc- and magnesium-compounds are used while the most commonly used as flame retardant is aluminium hydroxide [1, p 66-67].

Different solutions can be found for improving electrical conductivity of plastic parts such as use of metallic fillers, fillers with metallic coatings or even metallic mesh. They can also provide radiation prevention and protect from static electricity whereas PAN-based fibres also provide composites with same kinds of attributes since they conduct electricity [1, p 68-69].

Fillers can also be pigments or colours thus when used in small amounts, their effect on the structural features remain minimal. Organic pigments can even prove useful in increasing weather, light and heat resistance. Usually the pigments and colours are mixed into the resin before moulding [1, p 70].

A certain type resin mix-in additive is a release agent that helps demolding of parts after curing and it comes in liquid or powder form. They are mixed into the resin before moulding and they help to reduce cost and cycle times in automated processes. In hand lay-up the release agents are applied separately as a film or as in liquid form though they can have a negative effect on the physical aspects of the product when mixed into the resin. Typically release agents need heat for activation and are therefore suitable for heat enduring moulds. Typical mix-in curing agents are different stearates, stearic acid and alkaline phosphate in liquid form and soap, wax or silicone oil. The structural effects of fillers on thermoplastics can be found in Table 5.

Thermoplastic / Filler	Filler percentage [wt%]	Density [g/cm³]	Tensile strength [MPa]	Tensile modulus [MPa]	Elongation at brake [%]	HDT [°C]
PE-LD	0	0,92	10	210	500	35
Calc. chl.	40	1,26	16	900	220	-
Talc	30	1,14	16	600	40	-
Mica	30	1,16	13	440	46	-
PE-HD	0	0,95	27	1400	over 500	50
Calc. chl.	30	1,17	20	1900	9	-
Kaoline	40	1,24	26	2000	11	-
PVC (rigid)	0	1,36	60	2700	6-10	-
Calc. chl.	30	1,53	46	3200	8	-
Calc. chl. pre.	15	1,45	30-47	3100	6	-
Talc	20	1,48	34	3500	6	-
POM	0	1,41	63	2700	45	101
Talc	30	1,64	61	8600	3	-
PS	0	1,05	55	3800	4	86
Calc. chl.	30	1,3	15	2000	2	-
Talc	40	-	39	2600	1,6	-
PA6	0	1,13	64	1200	220	80
Calc. chl.	30	1,35	50	3000	30	60
PA610	0	1,19	60	1900	85-300	-
Talc	20	1,23	60	4000	5	-

Table 5. Structural effects of fillers on thermoplastics (1, p 72).

As seen in Table 5 the structural benefits gained with typical fillers are mainly in the area of tensile modulus and therefore the most notable benefits are cost reduction and improvements in other features such as flame retardance etc. Table 6 shows filler percentages in thermosetting plastic –based filler compounds and pastes, as instructed by Gurit Ltd.

Filler	Filler percentage of resin curing-agent mix (wt %)
Phenol microspheres (50 µm)	25-30
Glass micro spheres (40-80 µm)	35-40
Pyrogenic silica	2-5

Table 6. Filler percentage in resin curing agent –mix [1, p 73].

The resin – curing-agent mix described in the Table 6 is an example of a general recipe that has to be tailored according to the application.

In the future nanoparticles can play a significant role in plastics in filler and reinforcement purposes. They can be resourced from different materials such as metals, polymers and chemicals and if mixed in matrix plastics they can provide the composite with many of the same functions as other fillers. Nanoparticles can be mixed into both thermosetting and thermoplastics and they can be used with or without other additives. Carbon nanotubes are fullerene-like and they come in sizes ranging from 1-6 µm in diameter whilst a hundred times stronger than regular steel but at the same time the weight approximately one sixth of a steel particle of the same size. Nanotubes can be used for reinforcing as well as a semiconducting or conducting material in the matrix plastic.

2.2.3 Solvents

Solvents are normally used for controlling the viscosity of solvent based resins and for tool and mould cleaning purposes. Solvents are usually harmful and that is why performing the recommended safety measures should be taken care of. There are separate types of solvents for cleaning purposes according to the resin used and the compatibility must be checked from the supplier prior use. Same goes for using solvents as resin thinners [25].

2.2.4 Curing Agents

Curing agents are used for enabling the actual resin curing process. For polyesters, organic peroxides are used and the most common of which is ketone peroxide. Vinyl esters can use the same curing agents as polyesters. Commonly maleic anhydrides are used in case of epoxies. Usually resin providers have certain curing agents that are designed for the resin system to be used.

2.2.5 Fibres and Reinforcements

There are two main types of carbon fibres used in CFRPs; one is PAN-based and the other is pitch based. The PAN based fibres are more expensive but then again easier to work with since the pitch based fibres are stiffer and more fragile [1, p 81].

The reinforcing fibres can be discontinuous or continuous of which the discontinuous types are used in compounds for techniques such as SMC, BMC and RRIM. The aforementioned techniques are described in the corresponding chapters. Usually continuous fibres are used in the raw in techniques like pultrusion and winding. Commonly the continuous fibres are applied so that they form different types of woven, braided or unidirectional fabrics [1, p 127]. A table of fibres and their attributes can be seen in Table 7.

Carbon Fibre	Tensile Strength [GPa]	Tensile Modulus [GPa]	Density [g/cm³]	Tow weight [mg/m]	Cross-sectional area [mm²]	Elongation at brake [%]	Filament diameter [µm]
PAN-based:							
Grafil 34-700-12K	4,83	234	1,8	800	0,444	2	7
Grafil 34-600-48K	4,5	234	1,8	3200	1,776	1,9	7
Pyrofil TR30S-3K	4,9	235	1,79				
Pyrofil TR50S- 6K/12K/15K	4,9	235/ 240/ 240	1,82	400/ 800/ 1000	0,223/ 0,440/ 0,550	2,1/ 2,0/ 2,0	7
Pyrofil TRH50-12K/18K	4,9/ 5,3	255/ 250	1,81/ 1,82	800/ 1000	0,442/ 0,549	1,9/ 2,1	7
Tenax HTA40-1K/3K/6K	3,95	238	1,76	67/ 200/ 400		1,7	7
Tenax HTS40-12K/24K	4,3	240	1,77	800/ 1600		1,8	7
Tenax UTS50-12K/24K	4,8/ 5,0	240/ 245	1,79	800/ 1600		2,0/ 2,1	7
Torayca T300-3K/6K/12K	3,53	230	1,76	198/ 396/ 800		1,5	
Torayca T700SC-12K/24K	4,9	230	1,8	800/ 1650		2,1	
Panex 35-50K	3,8	242	1,81	3703			7,2
Pyrofil MR40-12K	4,41	295	1,76	600	0,34	1,5	6
Pyrofil MR60H-24K	5,68	290	1,81	960	0,464	2	5
Tenax IMS60-24K	5,6	290	1,8	830		1,9	5
Torayca T800HB-6K/12K	5,49	294	1,81	223/ 445		1,9	
Pyrofil MS40-12K	4,41	345	1,77	600	0,34	1,3	6
Pyrofil HR40-12K	4,41	395	1,82	600	0,329	1,2	6
Pyrofil HS40-12K	4,61	455	1,85	430	0,232	1	5
Tenax UMS40-24K	4,56	395	1,79	800		1,1	4,8
Tenax UMS45-12K	4,5	430	1,81	385		1,1	4,7
Torayca M40JB-6K/12K	4,4	377	1,75	225/ 450		1,2	
Torayca M50JB-6K	4,12	450	1,88	216		0,9	
Torayca M60JB-3K/6K	3,82	588	1,93	103/ 206		0,7	
Pitch-based:							
Dialead K1352U-2K	3,6	620	2,12	270		0,6	
Dialead K1392U-2K	3,7	760	2,15	270		0,5	
Dialead K13D2U-2K	3,7	935	2,21	365		0,4	

Table 7. Carbon fibre comparison. Figures are taken from the suppliers brochures.

It can be seen in Table 7 that the pitch-based fibres are usually heavier and have a higher tensile modulus and are therefore more suitable for applications where static loads are present.

2.2.6 Semi-finished Products

In hand lay-up process as well as in some automated processes semi-finished products are normally used to achieve high reinforcement percentages and ease of use.

The reinforcing fibres can be continuous as in fabrics or in discontinuous form as in moulding compounds and surface mats. Sometimes it is suitable to place each fibre filament separately to the mould to achieve directed stress distribution whereas there are also products that have both the resin and the fibres already bound together.

2.2.6.1 Fabrics

Fabrics can be woven or non-woven and can be unidirectional or multidirectional. Unidirectional fabrics are often laid on top of each other to form a multiaxial laminate structure. If directional structural attributes are not sought, surfaced mats made of discontinuous fibres can be used. In some applications both types of fibres can be combined [1, p 127].

Typically filaments in a fabric are bound together either mechanically or chemically by stitch bonding, needling or felting either with needles or water. Chemical binding methods usually take advantage of resins and that is why the binder should be chosen so that it is compatible with the matrix plastic [1, p 127-128]. The fabrics can incorporate thermoplastic binders so that the fabric can be conformed to the mould surface by applying heat.

Surface mats are typically used to control surface quality but they are not suitable for use in carbon-look applications. Woven fabrics are normally used for reinforcing purposes and in carbon-look applications [1, p 127-128].

Woven fabrics can be unidirectional or multidirectional where the former have most of the filaments in one direction whereas the latter can have the filaments in two or more directions. The surface density of CF fabrics can vary from 90-900 g/m² depending on desired attributes [1, p 128-129]. A table of correspondence of weave types and their attributes can be found in Table 8.

	Stability	Formability	Surface smoothness	Resin wettability
Plain weave	Good	Easy	Rough	Slow
Basket weave	↑	↓	↓	↑
Twill weave				
4 h. satin				
5 h. satin				
8 h. satin	Bad	Difficult	Smooth	Fast

Table 8. The correspondence of weaves and their attributes [1, p 129].

As seen in Table 8 the smoothest surface can be brought up by using 8 harness satin weave whilst it is the most difficult to form and has bad stability. Different weaves have their own structural features and specific appearances as well. The usual types of weaves can be found in Figure 7.

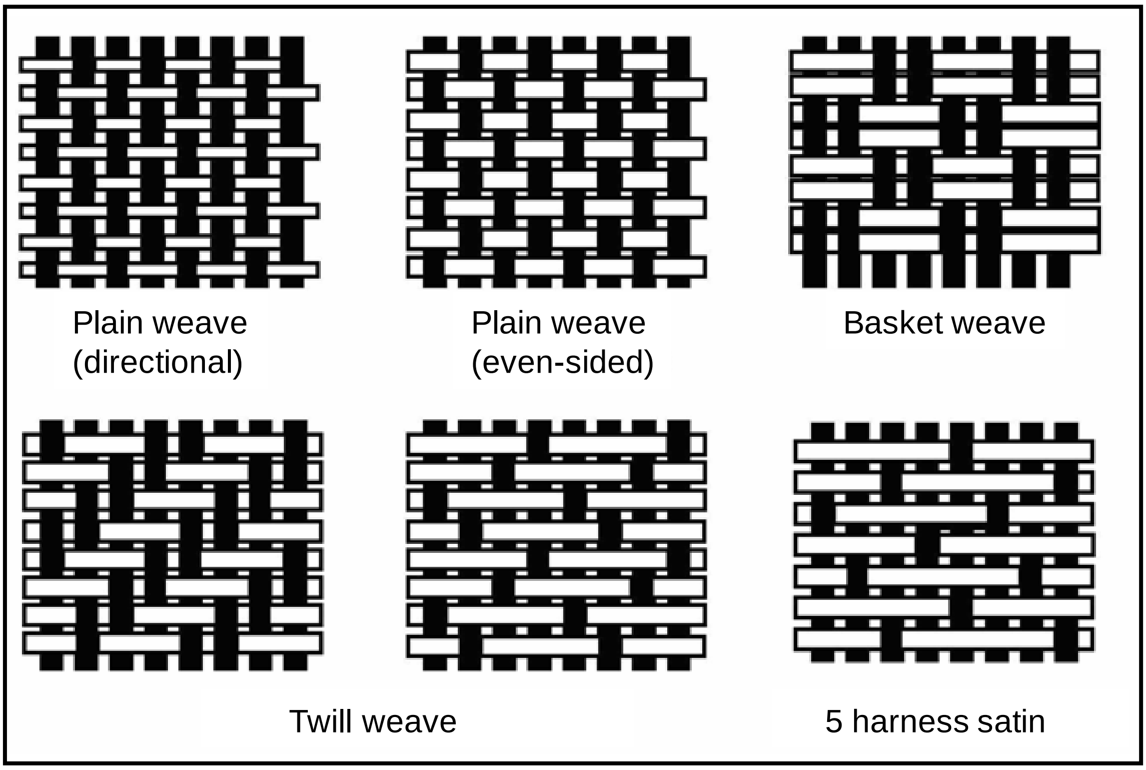


Figure 7. Common types of weaves [19].

The weaves seen in Figure 7 have all of the filaments in directions 0° / 90° whereas double bias fabrics have the reinforcements in for example +45°/-45° angles.

It is also possible to have the filaments in more than just two directions. These multiaxial fabrics can be manufactured by bonding fibre filaments together with the same methods that are used in the formerly mentioned fabrics. Common quadraxial fabric is formed of four layers of unidirectional yarns bound together with needling or stitch bonding using flexible binder yarn. The four layers can have the reinforcements for example in directions like 0°/+45°/-45°/90° and this kind of fabric is often called quasi-isotropic. The advantage gained is that the yarns do not cross each other and the layers can be arranged in any desired direction and it is possible to customize these fabrics by fitting additional layers as well to achieve the preferred functions. The multiaxial fabrics can be used in hand lay-up, RTM and other infusion techniques [1, p 131].

2.2.6.2 Prepregs

Prepregs consist of a fabric that is preimpregnated (**pre**im**preg**nated) with resin. The fabric can be of any desired form of woven to non-woven forms. The advantages are that prepregs already contain the required amount of resin and have a high percentage of reinforcements thus minimum level of scrap and high levels of structural features are gained [20, p 196-197]. The down side is that the when prepregs are cured in an autoclave the cycle times are slow and the part size is highly restricted by the autoclave chamber.

Prepregs can also be a formed of separate layers of reinforcement fabrics, incorporated with a resin film between the layers and the resulting products are also sometimes called semi-pregs. The advantage gained is good surface quality and that the part can be cured in an oven [18, p 90]. See Gurit Sprint CBS system for an example.

2.2.6.3 Preforms

Preforms are semi-finished products commonly made of fabrics that are cut to shape and then bonded mechanically by sewing or chemically to form a preform structure that is commonly shaped in a mould by heating and compressing. Preforms can incorporate inserts and other additional elements thus speeding up the manufacturing process whilst increasing fibre content and improving structural aspects. Preforms are typically used in RTM, VA-RTM and SRIM applications among others, in structural applications.

2.2.7 Core Materials

Core materials are used in sandwich structures, normally in panel-like structures. Typically they are in a foam form except for materials like balsa and honeycombs whereas syntactic foam consists of resin-microsphere mix. The core materials are applied between the reinforcing fabrics to make the parts lighter and thicker thus improving bending and shear strength. Common features and requirements for sandwich panels are:

- good weight specific stiffness and tensile strength
- low weight
- easy manufacturability
- heat or noise insulation

The core materials have to also meet the requirements of the application, such as water and fire resistance demands. Other requires features can be the ease of shaping, load bearing abilities, bonding methods and cost. Some examples of materials and their main characteristics can be found in Table 9.

Material	Density [kg/m³]	Service temp. range [°C]	Comp. Strength [MPa]	Comp. modulus [MPa]	Tensile strength [MPa]	Tensile modulus [MPa]	Shear strength [MPa]	Shear modulus [MPa]
PVC (Gurit PVCell)	60-200	-200 - 70	0,9 – 4,8	65 - 300	1,8 – 6,4	72 - 300	0,78 – 3,5	21 - 80
PUR (Hexcel Modipur US 569 B)	150	up to 170	2,05	77	1,26	94	1,02	35
SAN (Gurit T-foam)	71 - 143	up to 100	0,88 – 28,5	62 - 209	1,3 – 2,62	85 - 196	0,81 – 1,93	28 - 70
Syntactic foam (AMLITE LT64A)	540 - 660	up to 130	-	-	28	2300	-	-
Balsa (Gurit Balsaflex)	110 - 220	-60 - 150	10,1 – 17,5	3230 – 5200	9,4 – 13,8	2230 – 3930	2,0 – 4,3	146 - 206

Table 9. Examples of core materials and their attributes [35; 36; 37; 38; 39]

As seen in Table 9, balsa has supreme qualities compared to most of the other materials although since it is an organic material it is susceptible to fungus and insect attacks.

The organic nature of balsa also means that it is hard to achieve balsa core with uniform quality and structure.

Another category of core materials is honeycombs. They can be made of many different materials mainly by bonding thin sheets together and expanding the bonded structure to a honeycomb form or by using corrugated sheets that are bonded together. Commonly a sheet is also placed on faces of the honeycomb. An example of aluminium honeycomb manufacturing process can be seen in Figure 8.

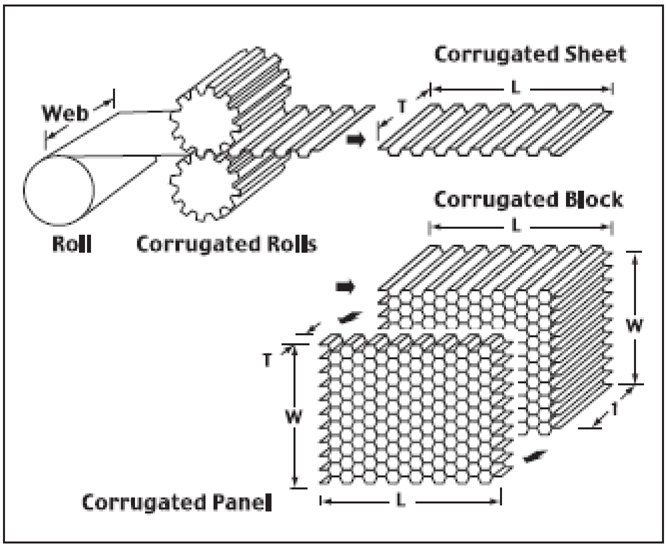


Figure 8. Manufacturing process of aluminium honeycomb [40].

As seen in Figure 8 the aluminium honeycomb is simple and light whilst providing the application with good structural integrity. When using metallic honeycombs with CFRP it must be noted that carbon fibre causes corrosion on the metals and it is therefore suitable to use metallic honeycombs that are coated with corrosion resistant coating. For example Excel provides their aluminium honeycombs with three different corrosion resistant coatings [40].

Honeycombs can also be made of aramid, fibreglass or other fibres in plastic matrix. A comparison of honeycomb materials can be found in Table 10.

Material	Density [kg/m³]	Crush str [MPa]	Compressive strength		Plate shear strength			
			Stabi-lized [MPa]	Mod [MPa]	L-Direction		W-Direction	
					Str [MPa]	Mod [MPa]	Str [MPa]	Mod [MPa]
Alumini-um	34-200	0,17-8,3	0,14-15	69-6200	0,22-8,6	83-1400	0,14-6,9	48-450
Aramid	40-140	-	0,52-12	41-620	0,31-3,7	14-262	0,16-2,1	6,9-120
Glass fibre	51-190	-	0,72-14	90-1800	0,50-5,6	28-380	0,28-3,6	17-190

Table 10. Comparison of honeycomb materials [40].

The data in Table 10 is acquired from Hexcel's material datasheets and represents the range of minimum figures of each attribute. It can be seen in the table that aluminium honeycomb has both the lowest and the highest densities but on the other hand glass fibre types have the best compressive strength. Due to structural differences in directions L and W the shear strength can vary significantly and must therefore be taken into consideration when the honeycomb is applied to the sandwich structure.

2.2.8 Inserts

Inserts in composite panels help in attaching the part to other parts by providing the composite panels with mechanical joining ability. The main requirements for inserts are due to corrosion factors and the differences in CTE between the jointed parts. This is the case especially when CFRP parts are joined to metallic parts such as steel or aluminium parts. The choices are to use corrosion resistant coatings or plastic sleeves in the inserts and corrosion resistant solution between parts when the CFRP part is attached to the metallic part [18, p 186]. In case of sandwich panels the surrounding area might have to be reinforced by means of filling honeycomb cells with the matrix resin or in other suitable way. A typical assembly of an insert in a honeycomb structure can be seen in Figure 9.

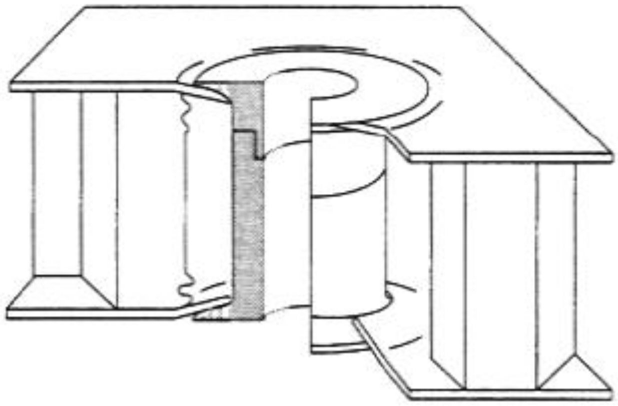


Figure 9. An insert in a honeycomb structure [41].

The insert type seen in Figure 9 is a thru-rivet plug and sleeve assembly from Alcoa´s catalogue that has a flush-type head. More examples of inserts for mechanical joining can be found in Appendix 4.

2.3 Storing

Depending on the product the storing requirements vary in conditions and storing time. The resins and raw fibres can usually be stored in room temperature whereas e.g. prepregs require storing temperatures below zero degrees Celsius. The appropriate conditions can be seen in the material data sheet provided by the supplier. Examples of storing conditions can be seen in Table 11.

Product	Temperature [°C]	Storing time
Gurit Sprint ST 85	-18 +18-22	two years two weeks
Hexcel 3501-6 (prepreg)	-18 +4 +18-22	12 months four months 10 days
HexFlow RTM6-2 (2-component RTM resin)	+5 (before mixing) -18 (max 5 kg can, after mixing) +23 (after mixing)	12 months nine months max 15 days
Gurit Ampreg 22 system (resin and hardener)	+10-25	two years
Gurit SF 70 Toughened Surfacing Film	-18 +18-22	two years four months
Gurit Eposeal 300 (gelcoat)	+10-25	two years

Table 11. Storing condition examples [42; 43; 44; 45; 46].

As seen in Table 11 most of the products have a long shelf-life in -18 °C and thus require storing in a freezer whereas e.g. resins have their suitable storing temperature above zero degrees. It can also be noted that the shelf-life decreases dramatically when the optimal temperature is altered especially towards higher levels.

2.4 Suppliers

Suppliers for different sectors of the CFRP manufacturing are listed in this section whether know-how, primary materials or equipment are sought. Examples of suppliers and their lines of expertise can be seen in Table 12.

Supplier	Services	Expertise	Closest location
Kevra Oy	Material and equipment distributor, engineering services, training	Raw materials, equipment	Finland
KG Enterprise Oy	Material and equipment distributor, engineering services, training	Raw materials, equipment	Finland
Jacomp Oy	Material and equipment distribution, engineering services	Raw materials, equipment	Finland
Bang & Bonsomer Ltd.	Material distribution	Chemicals	Finland
Composite Solutions and Innovations Oy (CSI)	Parts manufacturing, engineering services, training	RTM, Compression moulding, Hand lay-up	Finland
Gurit UK Ltd.	Material and equipment distribution, parts manufacturing, engineering services, training	Raw materials, Equipment, Class A panels, RTM, Autoclave, Prepreg lay-up, Vacuum moulding, Compression moulding, Thermoforming	United Kingdom
Hexcel	Material and equipment distribution, parts manufacturing, engineering services, training	Raw materials, RTM, Autoclave, Prepreg lay-up, Vacuum moulding, Compression moulding	Austria

Table 12. Examples of suppliers.

As seen in Table 12 the suppliers in Finland offer training in addition to their other services. Although not listed in the table number 12 there are a large number of service providers all around Europe that can provide with a wide range of services from raw materials to finished parts and processing equipment.

3 Equipment

Common equipment for mould building, curing, surfacing and mechanical tooling are introduced and presented in this chapter.

3.1 Moulds and Models

Mould building requires knowledge of the part to be built and of the manufacturing process to be used. The common aspects to be taken into account in mould designing are as follows [1, p 199]:

- size of the series
- curing temperature
- mould pressure
- dimensional accuracy and thermal expansion
- thermal conductivity
- the weight and stiffness of the mould
- cost
- special requirements of manufacturing techniques

The right ways of mould making have strong effects on the parts to be manufactured as well as in the serviceable life of the moulds not forgetting the economical aspects [1, p 199].

3.1.1 Models

When making a mould, a model is often used to aid the process. The material for model making should be cheap, easy to shape and have a good dimensional stability. The model does not necessarily have to be highly durable since it is not likely to make many moulds out of one model. The modelling materials for open moulds can be for example [1, p 199]:

- wood
- clay
- plaster
- resin paste

- foam

Plastics can also be used as castings, laminates or in tooled form. Cell foam plastics are as well used and there are also some specific model making materials. They are normally urethane- and epoxy – microsphere compounds whereas graphite can be used when high pressure curing is needed [1, p 199].

The higher mould pressures in closed mould techniques require high strength moulds. Moulds used in these applications are normally made of metals and manufactured without a model by mechanical tooling which in turn makes them durable but then again pricy [1, p 199].

3.1.2 Moulds

The mould material should be chosen according to the manufacturing technique to be used where the lowest requirements are in hand lay-up and low temperature methods and the highest in closed mould high pressure and temperature techniques. The principal criteria for the mould material are good wear resistance and temperature endurance thus it is advisable to have the moulds made out of a material that has CTE close to that of the part to be produced which in turn helps preventing dimensional deformations in the parts [1, p 199].

The moulds used for manufacturing small parts can be made of casted thermosetting plastics, commonly epoxy which is suitable for the application since it has moderate cure shrinkage. With different fillers and additives, epoxy resin can be modified for improved wear resistance, reduced weight and cure shrinkage and to manipulate CTE. Because CTE of pure resin is high, it is not suitable for big moulds [1, p 199].

One solution for making a mould is first making a rough basis for the mould from polystyrene and then coating it with epoxy paste that can be machined. After machining the mould gains its correct shape and thus can be finished for moulding parts. The advantage gained is that the mould is light and relatively easy to manufacture though on the other hand the polystyrene foam has reduced temperature endurance. If higher temperatures occur during the manufacturing process of a part a laminate of higher temperature endurance can be used between the polystyrene foam core and the epoxy paste. Thereby the polystyrene core can be removed before curing a part while still retaining the rigidity of the mould.

Silicone moulds can be used especially in prototype parts made with compression moulding since the method is fast and the mould making is easy and the material is cheap. The method requires a vacuum chamber to achieve the best results.

Reinforced plastics can often be used as an open mould building material of which the most used types are GFRP and CFRP materials. For manufacturing CFRP parts, the CFRP moulds are the more common and normally incorporate epoxy resin. The mould and the parts have a similar CTE which in turn helps in dimensional accuracy and that is why even parts with complex shapes can easily be manufactured. The moulds are more expensive compared to GFRP moulds, but are lighter and easily heated. They can even be used in autoclave when a suitable high temperature resistant resin is used [1, p 200-201]. A schematic for producing laminated mould can be seen in Figure 10.

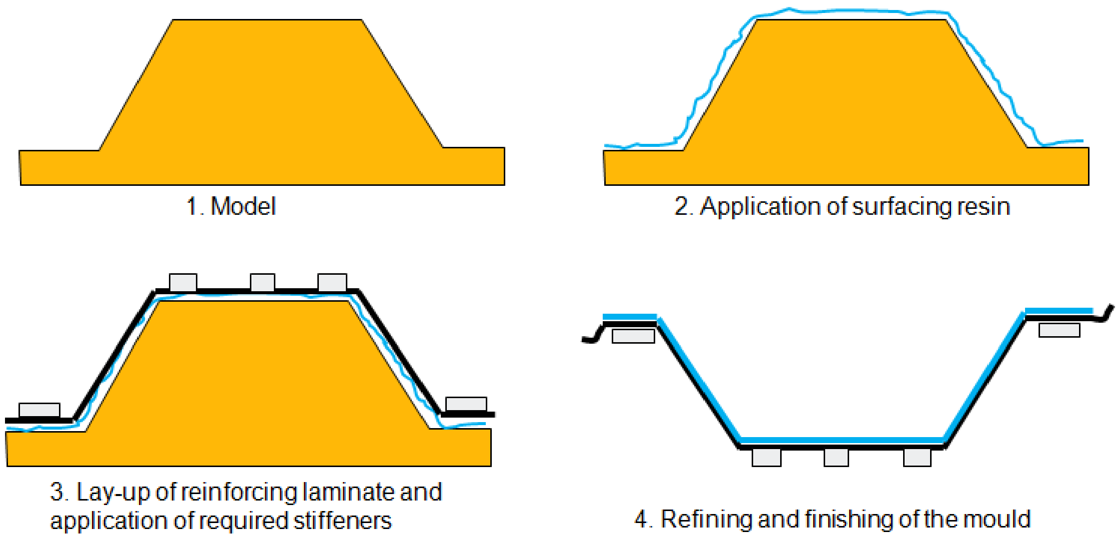


Figure 10. FRP mould making schematic [1, p 201].

As seen in Figure 10 the process of making a mould of FRP resembles to lay-up of the actual laminate and results in a thin and light mould that is easy to work with.

One thing to be considered when using laminated moulds is their anisotropic nature that for example can be seen as the differences in CTE between the direction of laminate plane or in the perpendicular direction. This can cause deformations in high temperatures which can be avoided to some extent by laminating the mould from smaller pieces so that the reinforcements are not continuous throughout the mould. Special mould techniques and different resins can also be used to prevent deformation. Sometimes interlaminar micro scale fractures are caused by temperature cycles that in turn reduce the service life of the mould [1, p 201].

When the series size increases the durability of the mould becomes more important thus metallic moulds are used. They are expensive and therefore the mould can be coated with metal. The metal coating can be either sprayed or applied by electrolysis and then reinforced with plastics, concrete or other inexpensive materials. In aforementioned techniques the advantages gained are durable moulds that are cheaper than the metallic ones while the down side is that when the metallic surface is sprayed the result is a somewhat porous surface that doesn´t suit all appearance requirements. In case of electrolysis coating, the surface becomes smooth but the technique is slow and requires skilled workers. These moulds made with metallic coating are suitable for prototype series, in case of sprayed coating, and for series production in case of electrolytic coating [1, p 201-202].

Ceramics can also be used as mould making materials. Conventional casted ceramics can be used as prototype mould materials where high curing temperatures are present. In addition to the heat endurance of the material it also has a low CTE and it is simple to work with but it results in porous surface and therefore needs to be treated. The moulds are also thick walled and are therefore heavy and slow to heat [1, p 202-203]. The ceramics can be used as a matrix instead of plastics and are normally reinforced by carbon fibres thus durable, thin-walled and low CTE moulds can be made. In high temperature cure processes also chemically fixed ceramics such as SiC matrix with ceramic and/or metallic particles can be used. These moulds are durable, light, fast heated and since they are isotropic, have excellent endurance for temperature changes [1, p 203].

In large scale series production, metallic moulds still prove to be the most suitable materials that can withstand high temperatures and pressures. The most typical mould materials are steel and aluminium of which aluminium is normally used in prototype and small series production in compression moulding techniques. It is cheap, but the softness of the surface and porosity, especially when it comes to casted aluminium, restrict its use in high pressure and large series production [1, p 203].

Steel is the most common mould material used in high temperature and pressure applications since it is dimensionally accurate and highly durable. On the other hand the high density of the material makes the moulds heavy and difficult to handle. Slow speed and high cost of tooling make the moulds expensive whereas the production and delivery can easily take months [1, p 203].

In dimensionally accurate high temperature applications Invar is commonly used as the mould material for series production and cast kirksite for prototype series. Invar has a low CTE whilst having exceptional wear endurance whereas cast kirksite alloy has the benefit of being reusable [1, p 203].

Graphite can also be used as a mould building material. Touchstone Research Laboratory has developed CFOAM carbon foam that can be used for mould building purposes and they claim it to have lower CTE and fabrication costs compared to Invar whilst being able to be used as an alternative to it. The tools made from CFOAM are light and easy to modify and repair while it also carries improved performance durability and increased part throughput since the moulds are light weighted [27]. A comparison of mould materials can be seen in Table 13.

Attribute	CTE $[10^{-6}/°C]$	Heat endurance [°C]	Thermal conductivity [W/m°C]	Wear resistance	Dimensional stability	Heat up rate	Surface solidity	Mass	Hardness, Rockwell	Young´s Modulus [GPa]	Cost
Plaster	9	100	1	bad	bad	slow	moderate	heavy	-	30	cheap
Invar 36	1	>500	10,5	excellent	excellent	good	moderate	heavy	73 Rb	141	expensive
Steel 4130	12	>500	40	excellent	average	moderate	good	heavy	32 Rc	200	average
Aluminium	20	>200	300	good	reduced	moderate	good	average	58 Rb	69	average
Graphite	3-5	>200	168	bad	good	slow	moderate	heavy	-	7	average
Chemically bonded ceramic	3-4	200-400	1,8	average	good	moderate	good	average	-	-	cheap
Cast ceramic	0-1	200-400	1,8	good	average	slow	bad	heavy	100 Rm	100	cheap
Nickel coat	13,5	500	75	good	good	good	good	average	95 Rb	205	average
Sprayed metal coat	-	150-200	75	average	average	moderate	good	average	-	-	average
CF/epoxy	4-9	150-200	1,7	average	average	fast	moderate	light	80-115 Rh	70	expensive
GF/epoxy	12-18	100-150	0,86	average	average	moderate	moderate	light	-	20	cheap
Cast epoxy	20-40	100-150	1	average	average	slow	good	heavy	90 Shore D	3	cheap

Table 13. Comparison of mould building materials (1, p 204-205).

As seen in Table 13 the choice of mould building material is always a compromise between attributes and must therefore be carefully chosen according to the application. The cost structure of moulds made of common materials can be found in Figure 11.

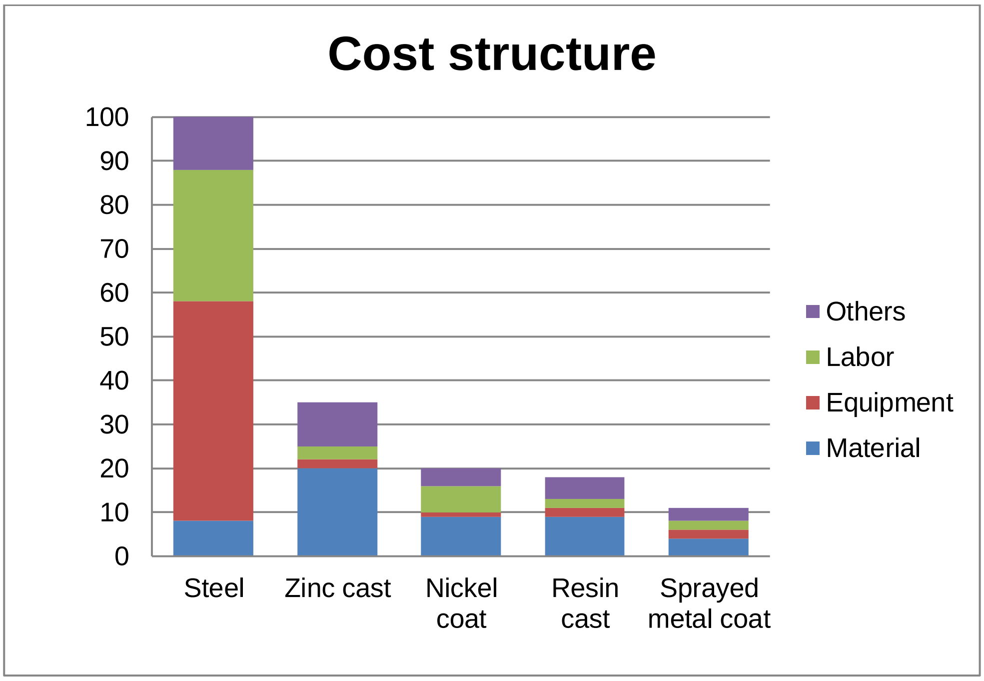


Figure 11. Cost structure of moulds of different materials [1, p 204]

It can be seen in Figure 11 most of the moulds price is due to material costs whereas in case of steel moulds the labour and equipment play a significant role in cost structure. Also the cycle life of moulds is one thing to be taken into consideration and a chart on the matter can be seen in Figure 12.

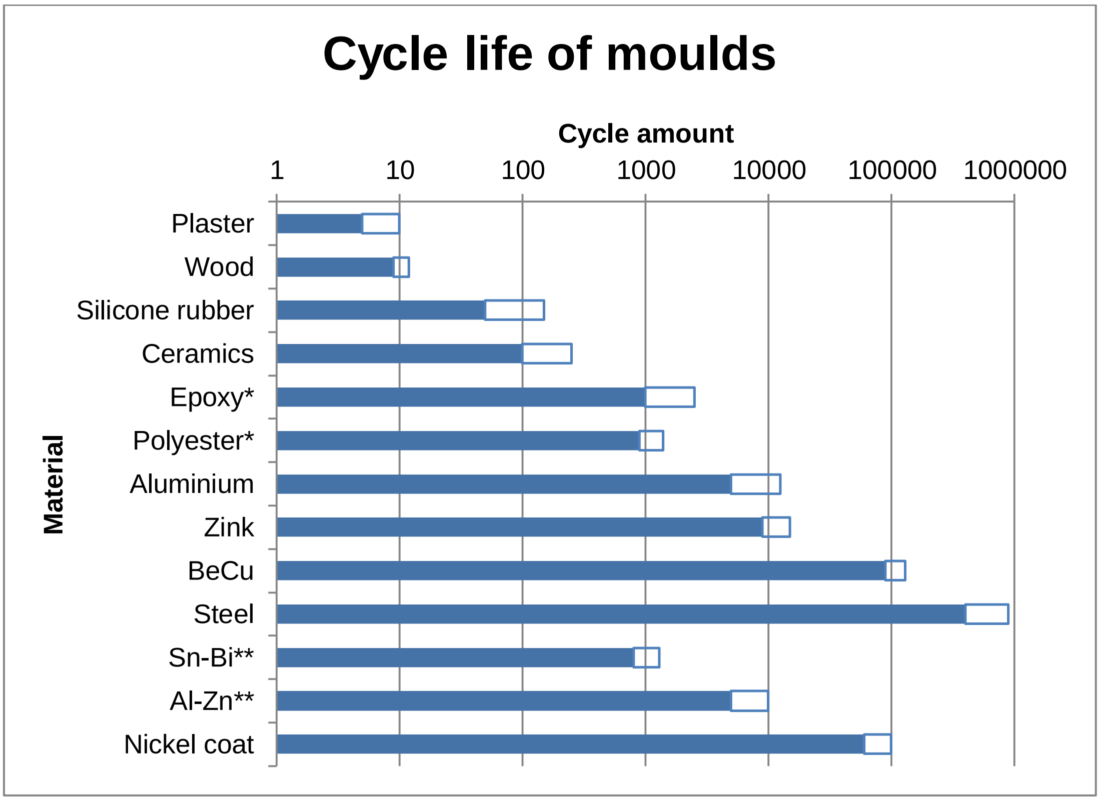


Figure 12. Cycle life of moulds of different materials, *reinforced, **sprayed metal [1, p 20].

As seen in Figure 12 the smallest cycle life is experienced with plaster moulds and on the other hand steel and other metallic moulds have the highest cycle life.

3.1.3 Mould Structures Listed by Manufacturing Technique

Main principles of mould designs can be found in this chapter.

3.1.3.1 Open Moulds

Open moulds are commonly used in hand lay-up and spray-up techniques where they can be either male or female moulds and can consist of one or more parts. Usually moulds are made of multiple parts when the shape of the mouldable part is complex. Typically a release angle of couple of degrees and moderate chamfers are good basic rules of designing [1, p 206].

Usually low temperatures and pressures are present when open moulds are used and that is why the most suitable materials are GFRPs based on polyester or epoxy. For small parts the mould materials usually do not need reinforcements whereas bigger moulds typically use stiffeners or consist of a sandwich structure. The moulds might have a need for thickening to prevent read-through of stiffeners [1, p 206].

The laminates used in the moulds are commonly quasi-isotropic along the laminate plane. To reduce cost and speed up the lay-up process, fillers can be used in the mould material. On the mould surface a specific mould gelcoat can be used that is thick and hard and therefore can easily endure sanding. A layer of reinforcements can afterwards be applied, such as a surface mat or thin fabric as it improves the surface quality and prevents read-trough of the reinforcements in the part to be manufactured [1, 206].

Vacuum injection moulds can be of the same kind as the hand lay-up moulds though in addition wider flanges must be used in the edges of the mould to provide enough space for the vacuum bag and resin inlet fitting. The mould has to be perfectly sealed which can be tested by applying vacuum to it before the actual lay-up process. If a flexible counter mould is used, it can include the required sealants and resin inlets and therefore speed up the lay-up process significantly [1, p 206].

A mould can also be made with 3D-printer which reduces the required fabrication time from nearly two weeks to a couple of days and thus greatly decreases the time consumed in mould designing [34]. Surface quality can be good, though it is recommended for the mould to be sanded prior use.

3.1.3.2 Other Moulds in Brief

Table 14 provides with information of moulds in brief for other than hand lay-up.

Technique	Mould material	Heating	Other
Compression moulding	FRP, cast resin, metal coat, metallic mould, ceramics	Through clamping elements or heated mould	In cold compression, no heating.
SMC	FRP, cast resin, metal coat, metallic mould	Through clamping elements or heated mould	No cooling required
RTM	FRP, metal coat, metallic mould	Through clamping elements or heated mould	High pressures
RIM	FRP, cast resin, metal coat, metallic mould	Through clamping elements or heated mould	Low pressures
Prepreg (autoclave)	FRP, cast resin, metal coat, metallic mould, ceramics	Through air (autoclave)	Heating ramp-up, mould includes multiple parts
RFI, Prepreg (non-autoclave)	FRP, cast resin, metal coat	Through air (oven)	Open mould, vacuum bag
Pultrusion	Metallic moulds, mainly steel	Heated mould elements	High temperature and pressure

Table 14. Information of moulds in brief [1, p 206-214].

In Table 14 most of the techniques can use FRP moulds for prototype series production whereas metallic moulds are mainly used in series production. The heating method also sets some requirements to the mould design since they need to incorporate heating elements in some cases.

3.2 Curing

Curing can be carried out in room temperature but in most cases requires certain equipment. The main types are ovens, electrical and liquid heating systems and sometimes microwaves are also used.

The basic components of an electrical system are heating wires or cartridges, temperature sensors and a control interface. SPE Automotive has researched heating through CF reinforcements in the part where the reinforcements are attached to an electrical wire and then electricity is conducted through the fibres and thus heating the laminate. This enables efficient heating by restricting the heating to the part itself [28]. Certain types of electrical heating apparatus can be found in Figure 13.

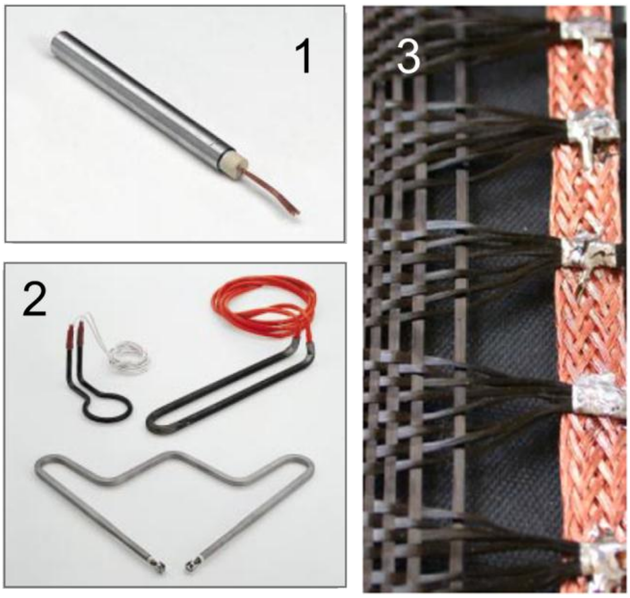


Figure 13. Electrical heating equipment [28, 29].

As seen in Figure 13 the part can be cured with a variety of equipment. The first one is a heating cartridge that can be applied to the mould structure as well as number two which is a tubular heater. The tubular heater can be bent to a desired shape so that in can be used even in a complex shaped mould. The number three is the SPE Automotives´ heating system which heats the laminate through the reinforcements.

There are also liquid systems that can use either oil or other liquid and can incorporate cooling as well. The main parts are heating/cooling ducts, temperature sensors, circulator, heater and control interface. For example Tricool Thermal can provide with following equipment [30]:

- water heating system, up to 95°C
- pressurised water heating system, up to 160°C
- oil heating system, up to 350°C

Electrical and liquid heating elements can both be applied to the mould or to the clamping devices. The electrical heating device can also be a film that is applied on top of a laminate in an open mould while in all cases suitable insulation has to be taken care of.

Oven curing is commonly used with open moulds and usually a vacuum bag is also used to debulk excess air from the laminate. Autoclave is a combination of pressure chamber and an oven whilst both oven and autoclave heat the laminate commonly through convection. The main differences between oven and autoclave curing can be seen in Table 15.

	Pressure	**Temperature**	**Cost of equipment**	**Moulds**	**Notes**
Autoclave	High	High	High	Multiple parts, expensive	High surface quality on both sides
Oven	Low	Low	Relatively low	Open mould, cheap to expensive	Vacuum bagging, only one high quality surface

Table 15. The main differences between autoclave and oven.

As seen in Table 15 the oven curing is less expensive since it uses cheaper equipment and both lower pressure and temperature. Nowadays even parts cured in oven can have excellent surface quality and high percentage of reinforcements while cheaper and faster to manufacture than parts made in autoclave.

3.3 Surfacing

Surfacing can be carried out with suitable coating and sanding and there are also surfacing films that do not need further refining. The coating can be resin-like filler, mostly epoxy or polyester based, or surfacer paint. Sanding should be carried out between layers of filler or surfacer. Sanding paper grades commonly used are as follows [1, p 102]:

- before painting, grades 180-220
- after filling, grades 80-120
- between surfacer paint layers, grades 180-220
- after surfacer and before topcoat, grades 220-600
- If required more finer grades are used before topcoat, grades 1200-1600

The resemblance of different types of sanding papers can be found in Table 16.

Water sanding paper	60	100	120	220	320	400	800	1200
Dry sanding paper		80	100	180	280	400		
Sand paper		80	90	100	180			

Table 16. Resemblance of different sanding papers [1, p 103].

As seen in Table 16 the sanding paper grades differ from each other and thus must be chosen according to specified grade or its equivalent.

The surface should always be cleaned before applying a surfacing layer or after sanding. The easiest way to determine whether the surface is free of contaminants is by pouring water on it. If the water generates droplets, there are still contaminants on the surface. Water is also used for removing dust from the surface and afterwards care should be taken that the surface is clean and dry after surfacing [1, p 102].

Surfacing films are useful for quickly gaining a smooth surface finish and as an example 3M provides with Scotch-Weld Low Density Composite Surfacing Film AF 325 that is applied straight to a release agent treated mould surface. The film is designed to be used especially with prepreg lay-up and is compatible with most epoxy resins [31].

One sort of surfacing film is a peel ply that is commonly used when the laminate is to be secondarily bonded to another part. The peel ply gives the part a special textured surface that is ideal for bonding and it is designed to be peeled off from the surface after curing. Peel plies are used with parts made by hand lay-up for best results, since they tend to absorb resin from the laminate. Some prepreg peel plies or finely woven sheets are developed to prevent resin absorption [32] when needed. An example of peel ply can be seen in Figure 14.

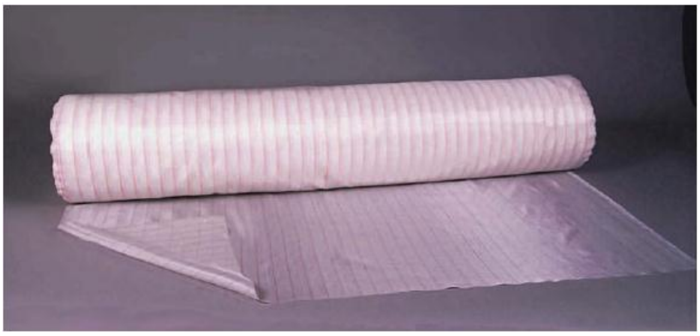


Figure 14. A roll of peel ply [32].

In Figure 14 the red warp in the peel ply helps the detection in cured part. An example of a parts surface after removing the peel ply can be seen in Figure 15.

Figure 15. Parts surface after removing the peel ply.

As seen in Figure 15 the finished part gains a textured surface after the use of peel ply which in turn improves the adhesion between bonded parts.

3.4 Machining

Almost all of the same methods that are used with metals are also used in machining CFRP parts. The main difference is in the behaviour of the part to be machined since the material is not homogenous and the fibres tend to have high abrading effect on the tools made of conventional materials. To achieve best results, special tooling must be used for composite parts. Several other important matters when tooling composites are [1, p 214]:

- waste matter must be removed properly, since it often consists of small particles especially when grinding and cutting
- when cutting a laminate, it should be supported adequately
- cutting speed should be slow enough to prevent delamination
- the heat build-up in the laminate during tooling processes must be noted since it can damage the laminate

3.4.1 Cutting

Cutting equipment can be a band saw or a circular saw (or disk) with a diamond coating, ultrasound, laser or a water jet cutter. When using a saw kind of cutter, it must be noted that high risk of delamination and heat build-up are present [1, p 214-215].

Ultrasound cutting is the fastest among the aforementioned cutting techniques and it uses a cutter that resonates in ultrasonic frequencies thus it has low friction between the cutter and the laminate. It is especially useful when cutting prepregs and reinforcements at higher speeds and precision compared to conventional cutting methods [1, p 216]. An example of ultrasonic cutting device can be seen in Figure 16.

Figure 16. An ultrasonic cutting device [33].

The main parts of ultrasonic cutter seen in Figure 16 are oscillator and hand piece which incorporates the cutting blade.

Typical laser used in composite cutting applications is CO_2 laser. It vaporises the material to be cut and therefore sufficient ventilation should be taken care of. Laser cutter is fast and accurate but can cause heat build-up in the laminate. Usually when cutting CFRP of 3 millimetres thick, an area on the cut edge of one millimetre wide is damaged by heat [1, p 216-217].

Water jet cutting is accurate and the cutting slot is narrow and actual cutting can be started from any location on the surface. Water jet cutting doesn´t cause heat build-up, hazardous vapours or dust while on the other hand the down sides are that the water can penetrate to the laminate or reinforcements when cutting laminates or reinforcements. Sometimes when used with sandwich structures or thick laminates the water jet tends to spread and causes edges that are not permissible. The cutting speeds for common cutting techniques can be found in Figure 17.

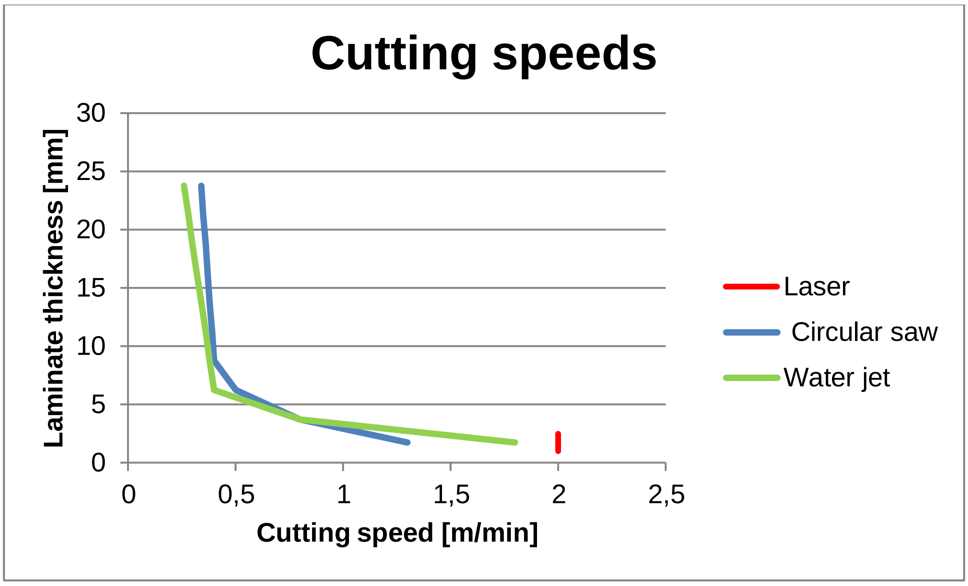


Figure 17. Chart of cutting speeds relative to laminate thickness [1, p 214-218].

It can be seen in Figure 17 that the cutting speed can be variable in case of circular saw and water jet cutter but in case of laser cutter the speed is constant regardless of laminate thickness.

3.4.2 Grinding, Drilling and Die-cutting

Grinding equipment can be sanding papers or grinding wheels and when using grinding wheel, high speeds such as over 20.000 RPM should be used [1, p 218]. Usually diamond plated tools are the best for grinding and drilling since they are the most durable types. When drilling CFRP parts special purpose-built tools should be used such as shown in Figure 18.

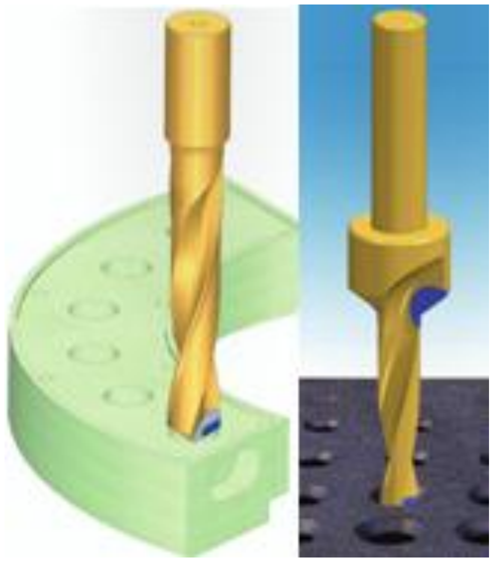


Figure 18. Drilling tools for CFRP by Lach-Diamant.

In Figure 18 both types of drilling tools shown have diamond coating in the surfaces that are susceptible for the biggest amount of abrasion, a positive cutting angel and are specifically designed for cutting CFRP.

Die cutting is used when large quantities of similarly shaped parts are manufactured though the technique is not suitable for large sized parts. It can be used to cut prepregs or fabrics to build preforms and stiffeners etc.

4 Manufacturing Techniques

Hundreds of manufacturing techniques exist nowadays and new ones are developed all the time mostly by combining old methods. Different methods suit different applications but in automotive applications the cost and cycle times as well as surface quality are the most important factors in choosing the right type of process. The most suitable techniques for automotive applications are explained in the following chapters.

4.1 Hand Lay-up

Hand lay-up is a common term for techniques that can be applied by hand. It can be divided into three main categories; wet, dry and spray lay-up and they are suitable for manufacturing of prototype series parts.

4.1.1 Wet Lay-up

Wet lay-up is a technique where the fibre fabric and the resin with its additives are applied to the mould separately by hand, layer by layer. The typical resins used are epoxy, polyester, vinyl ester and phenolic. When using a wet lay-up method it must be noted that the resins and solvents used are at least somewhat harmful chemicals. The lay-up procedure is shown in Figure 19.

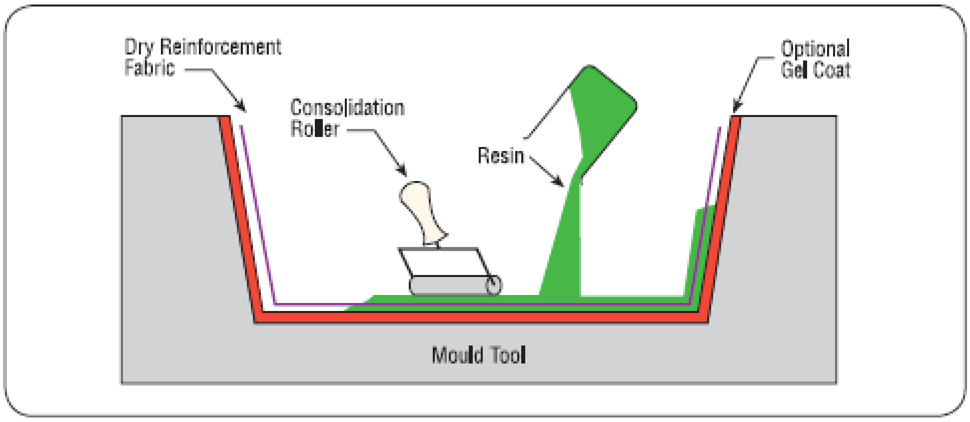


Figure 19. The wet lay-up process [23].

In Figure 19 the process is as follows: first an optional layer of gelcoat is applied to the finished mould, next the dry fabric is laid on top of the gelcoat and then the resin is poured into the mould and a consolidation roller is used to debulk the laminate of excess air thus solidifying the laminate. It must be noted that the process in the figure is a simplification of the actual process.

The suitable conditions for this process are based on the instructions given by material providers and as an example, Gurits Ampreg 22 epoxy laminating system has its optimal working conditions in the temperature 18 – 25 °C and a maximum relative humidity of 70 %. If higher temperatures occur, the working time is reduced.

Normally Ampreg 22 resin is mixed with Ampreg 22 curing agent and the curing agents in this case are labelled as fast, standard, slow, extra slow, 14 hour or high Tg and they can be mixed together to form an intermediate solution. The mixing ratio should always be measured with electric scale or other precise methods to achieve the correct result.

The ingredients of the mixture should also be mixed well with a vessel especially made for the purpose. The mixing ratios by weight and by volume can be found in Table 17.

Ampreg 22 resin	Ampreg 22 hardener/curing agent
100 units by weight	28 units All hardeners
100 units by volume	32 units Fast
100 units by volume	33 units Standard or Slow
100 units by volume	34 units Extra Slow or 14 Hour
100 units by volume	29 units High Tg

Table 17. Gurit Ampreg 22 lay-up system resin-hardener mixing ratios.

As seen in Table 17 there is a difference between mixing the substances by weight or by volume and since the mixing ratio defines the attributes of both curing behaviour and structural features it is of the essence to check which method applies.

To aid mixing the resins and curing agents, they can be provided with pigments so that it is possible to visually indicate the proper mixing of the components. For example the resin can be yellow and the curing agent blue and thus after proper mixing the result can be seen as a green colour. After mixing the compound is poured into a shallow tray, similar to a painting tray which is done to reduce the exothermic heat build up and improve pot life.

To prevent the resin from flowing on steep angled or vertical surfaces a thixotropy additive can be mixed into the resin and as an example Gurit has Ampreg Pregel for the purpose. It is a thixotropic resin that when mixed with hardener can be used instead or mixed to a resin to modify drainage and flow. It can also be used for bonding preformed laminate components.

Depending on the mould used, demolding is aided by applying a suitable amount of wax, usually five or six layers being enough. Polyvinyl alcohol should be used in complex or slightly rough surfaced moulds and after the treatment the surface should be polished without removing the release agent. A test laminate is always the best way to determine the right way and amount of release agent to be used.

Gelcoat and topcoat are commonly used to act as the visible surface of the part and are therefore applied to the mould after the release agent treatment. Both of them can be clear or pigmented and are sorts of resins as well. They are applied by spraying or by brush whereas topcoat usually requires additional sanding before the actual lay-up can be performed. More on these two coatings can be found in the corresponding chapters.

The mix of resin and its additives are commonly applied by a foam roller from a roller tray or sometimes with a brush. Accuracy in reinforcement percentage can be brought up by applying measured ratio of resin-mix and reinforcements to every layer. Usually it is accurate enough if maximum weight per square meter of resin applied is the same as the desired weight of the finished product per square meter. The tools used for resin application should be cleaned with acetone in case they are to be reused.

If the laminate is going to be adhesion bonded to another part after curing, Gurit advises to use a peel ply that in turn provides the laminate with two functions, preventing the surface from contamination and it gives the laminate a textured surface that makes it easier to bond. It is applied during the lay-up process to the laminates surface to be bonded and it is peeled off just before bonding. Any peel ply should be tested for appropriate release and that it doesn´t leave any residues that could affect adhesion.

The consolidation of the laminate can be carried out in several ways, first being by hand using a paddle roller and the second way being the use of either vacuum or pressure bag. When using high vacuum with slow curing agent, the vacuum should not be applied before 50 % of the working times has passed or else resin starved laminate and excessive flow might occur and if vacuum has to be applied in an earlier stage, only 30 – 50 % vacuum should be used. The process of vacuum bag usage can be seen in Figure 20.

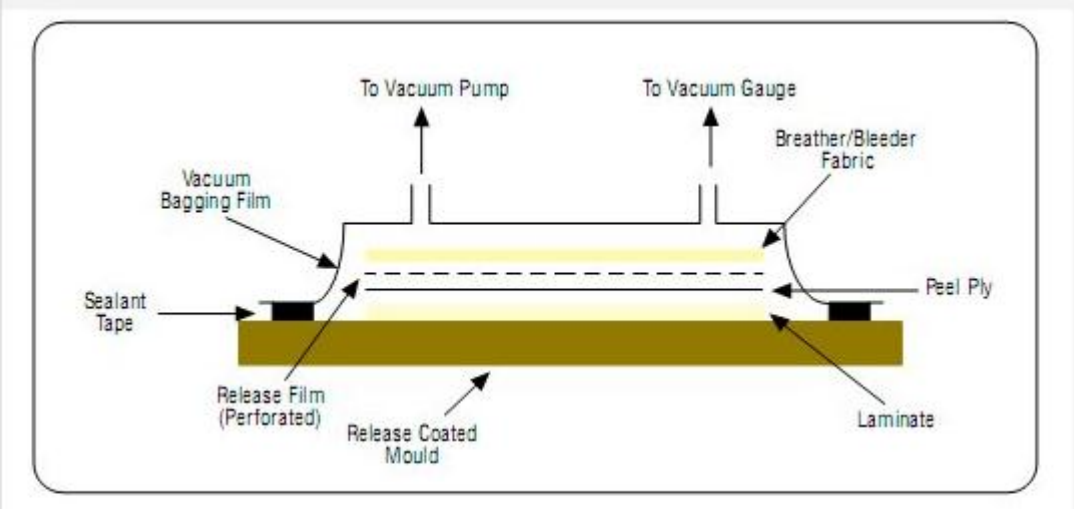


Figure 20. Vacuum bag process [4].

As seen in Figure 20 the vacuum bag technique requires also other ancillaries such as sealing and pumping equipment that can usually be obtained from the same source as the bag itself.

Heating can be carried out by space heaters whilst using an insulation tent or with heated blankets with insulation over. When Ampreg 22 resin is used, Slow or Extra Slow curing agents are best suited for vacuum curing. When the laminate is still wet, it should not be exposed to vacuum over 80 %, that is to say vacuum pressure of 0.8 bars. For Ampreg 22 resin system, Gurit recommends Tygavac vacuum bags and ancillaries.

If core materials are used for laminating a sandwich structure, Gurit recommends Corecell SAN closed foam, PVCC foam, Nomex honeycomb and engrain balsa for use with Ampreg 22 resin system. The core material can be applied between layers or on top of the laminate. Further information on the materials can be found in the core materials section.

The curing process can be carried out in ambient or elevated temperature and elevated temperature post-cure is advised for reaching excellent mechanical features after cure in ambient temperature. The curing must be carried out in temperature of at least 18 °C and during a time period of at least 48 hours with slow and extra slow curing agent and at least 16 hours when using fast or standard. To consider the laminate properly cured in ambient temperature, it should be allowed to cure for 14 days when using Fast, Standard or Slow hardener. The moulding should be kept in a warm dry place during this period whereas elevated temperature post-curing is recommended when Slow, Extra Slow or High Tg hardeners are used. The post-curing should be carried out before demolding and Gurit recommends curing temperature of a least 55 °C if 14 Hour hardener is used.

When the elevated temperature cure is applied the laminate will gain a significant increase in mechanical properties as an example the Ampreg 22 resin system will achieve the same kind of properties with either five hours at 70 – 80 °C or 16 hours at 50 °C. As an exception, the 14 Hour hardener requires 16 hours at 55 °C fort post-cure. The post-cure should be carried out right after laminating when possible but if it occurs that the laminate is demolded before post-curing, it should be supported and the supports should not be removed until the part has cooled down properly. Either way it is recommended to post-cure the part before finishing or painting.

Further information on different resin systems and ways of working with them can be found from the suppliers. As an example of user guide, see Ampreg 22 resin system user guide in appendix 3. The hand lay-up process in a nutshell is as follows:

1. Mould surface treatment and cleaning
2. Release agent or film application
3. Optional gelcoat or topcoat application
4. Application of dry reinforcements
5. Wetting of reinforcements with resin, debulking
6. Optional core material application
7. Optional repeating of steps 4 and 5
8. Curing in ambient or elevated temperature
9. Optional Post-cure
10. Demolding and finishing

The number of reinforcement-resin –layers applied can be chosen as desired, even on top of each other, keeping in mind that the thickness of the laminate affects the curing behaviour of the part. Common defects in had lay-up products and the possible causes are listed in Table 18.

Defect	Possible cause
Surface crack	Stress overload caused by excess heat or external load
Star like shape in the surface	Impact
Delamination	The surface of the laminate hasn´t been roughened before the lay-up of the following layer Too small radii in corners or too thick layer of lay-up applied at one time Interlaminar shear strength limits exceeded Reinforcements aren´t moistened properly
Burn mark	Too thick layer of lay-up applied at one time
Whiteness	Reinforcements are damp The binder or coating of the reinforcements is not compatible with the resin used The acetone used to clean the tools has ended up in the laminate
Redness	Too much curing agent
Air bubble	Insufficient debulking
Sticky or uncured laminate	Resin without accelerant Wrong measuring of accelerant or curing agent Curing temperature too low Reinforcements are damp Air humidity too high Too thin layer (if polyester resin) The resin used requires postcuring
Resin accumulation	Excess use of resin Not enough thixotropy-additive
Twisted laminate	Asymmetric lay-up sequence
Part distortion	Laminate hasn´t been in the mould long enough

Table 18. Common defects and their possible causes [1, p 158]

As can be seen in Table 18 the hand lay-up process has many parameters that can cause deformations in the resulting part and thus requires skilled workers to gain repeatable good results.

4.1.2 Dry Lay-up (Prepreg)

Because of the nature of the prepreg sheets the laminate will have higher percentage of reinforcement than the wet lay-up parts which is a result of a precalculated amount of resin used and the use of vacuum film compression in the curing process. To make it possible to bend the prepreg sheets over complex shapes the sheet can be heated and softened with a warm-air heater. Otherwise the hand lay-up of prepregs is quite similar to the wet lay-up. In prepreg lay-up the laminate should be debulked after every one to three layers. It is possible to use core materials in prepreg lay-up as well.

Prepreg structures are commonly cured in autoclave for best results. In this method the size of the part is strictly restricted by the size of the autoclave chamber. The autoclave method is suitable for prototype series production due to its high costs and long ccle times.

There are also ways of curing prepregs in a non-autoclave way. Gurits Sprint CBS (Car Body Sheet) uses sheets that consist of surface film, reinforcement layer, resin core film and a second reinforcement layer. The Sprint CBS system provides the parts with class-A surface, optimized weight and cost [24]. The Sprint CBS sheet can be seen in Figure 21.

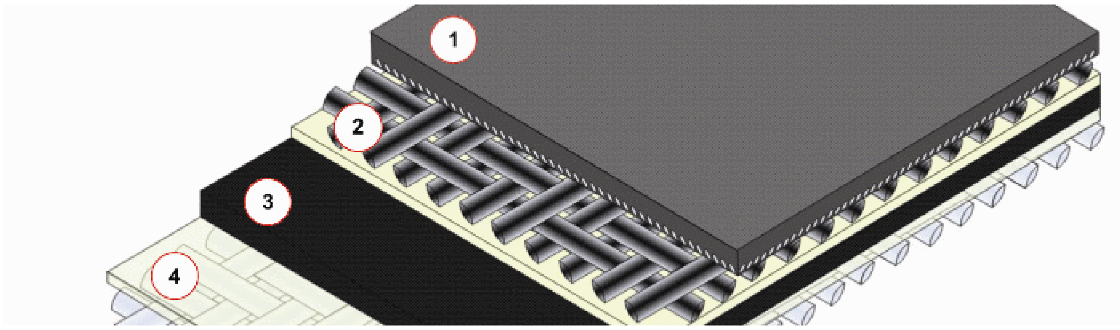


Figure 21. Gurit Sprint CBS [24].

In Figure 21 the structure of the sheet is numbered as follows: number one is an in-mould surface film, number two is the first layer of reinforcements, number three is the resin core and number four is the second layer of reinforcements. The in-mould surface film acts as the visible surface of the resulting part.

4.1.3 Spray-up

In spray up process the resin and reinforcements are sprayed to the mould by hand but the process can be as well automated in some applications. The gain of the technique is that it has les opportunities to be carried out unsuccessfully, although it still requires a great amount of expertise. If done by hand, it is difficult to maintain equal thickness in the walls but if the production is fully automated, it is not an issue.

Usually the reinforcements used are chopped or milled fibres that are mixed to the resin which includes the curing agent and the accelerant. The spray-up is faster method than the wet lay-up and is suitable for prototype part manufacturing where there are no high requirements of structural rigidity. The process can be seen in Figure 22.

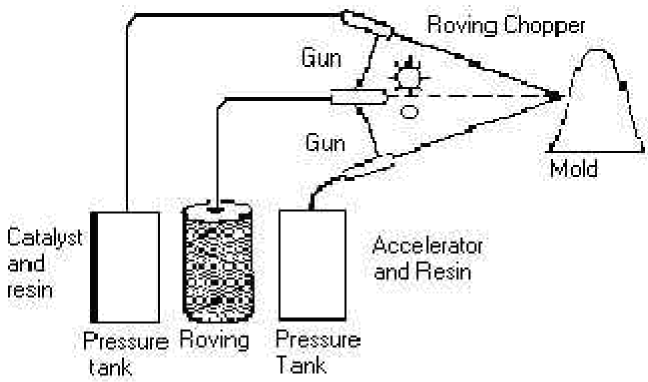


Figure 22. Spray-up process [6].

In the process shown in Figure 22 the roving is chopped and mixed with the resin and then the whole mixture is sprayed to the mould.

4.2 Compression Moulding

There are several compression moulding techniques for automotive parts manufacturing of which the most used are explained in the following chapters.

4.2.1 BMC

BMC is used in compression moulding as well as in injection moulding, mostly for interior parts since the surface quality is relatively good. The structural attributes are rather low since the BMC does usually have only 15-30 wt% of reinforcement [1, p 141]. BMC consists of matrix plastic, chopped fibre, filler, pigment, curing agent and shrinkage preventing agent and sometimes a flame retardant is also used. It is suitable for small or medium series production. The compression method of BMC can be seen in Figure 23.

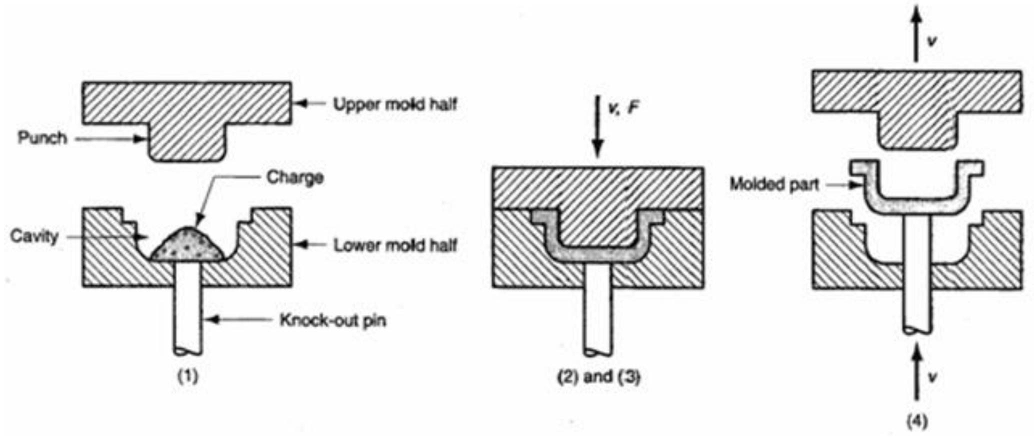


Figure 23. Compression moulding process [10].

The process in Figure 23 goes as follows: First the compound is applied to the mould then the mould is closed with pressure and last the moulded part is pushed out of the mould.

4.2.2 SMC

SMC is a sheet-like reinforced plastic compound that normally includes filler and other required additives. It is formed by compression moulding. It is suitable for series production of relatively large sheet-like parts. The advantages of the technique are that the parts are dimensionally accurate and relatively large. In addition one part made of SMC can replace multiple parts made of sheet metal. SMC is used in for example trunk lids and fenders. The compression method of SMC is quite similar to BMC except the fact that SMC is a sheet. An example of a part made of SMC can be seen in Figure 24.

Figure 24. A cylinder head cover made of SMC [11].

As seen in Figure 24 SMC is quite a flexible material and the parts made of it can incorporate complex shapes even though it is a sheet-like material.

Compression moulding of prepreg is quite similar to SMC. Prepreg sheets can have up to 60 v% of reinforcements and are suitable for parts that are necessary to have good strength attributes [1, p 145]. The method is suitable for series production.

4.2.3 Film Compression

In film compression a prepreg sheet is compressed into the mould between two thin films usually made of polyimide. Then the prepreg is condensed by vacuum and heat. The final moulding is carried out by over pressure [1, p 183].

The advantages of the technique are short cycle time and inexpensive moulds. The mechanical attributes of the parts made with film compression are good since it uses prepreg sheets. Film compression enables the making of thin walled complex planar structures. A film compression process schematic can be found in the Figure 25.

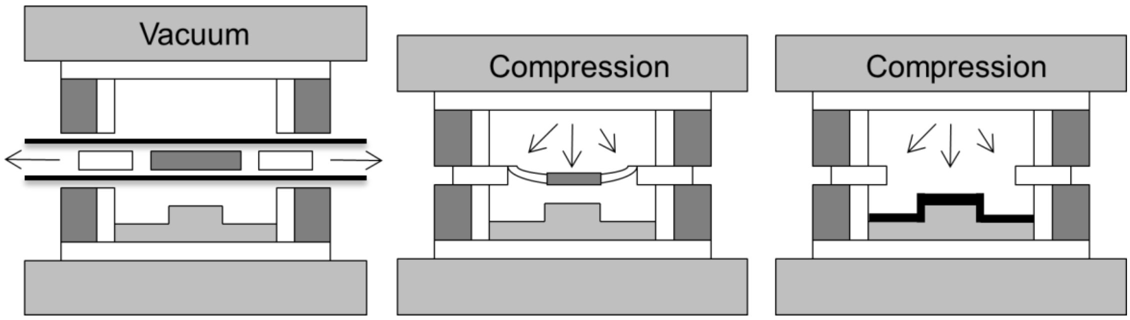


Figure 25. Film compression process [1, p 183].

In Figure 25 the first step of the film compression process is when a prepreg sheet is attached between two plastic films with vacuum and heated. After all of the excess air is removed the prepreg is compressed to the surface of the mould.

4.3 Injection Techniques

The thing in common between the injection techniques is that the resin is injected to the mould with positive pressure or vacuum. The reinforcements can be fabrics, chopped or milled fibre normally mixed with the resin or a preform. The resin can be attached to the preform as a resin film or in some other form. The focus in this chapter is in the positive pressure injection techniques.

In vacuum injection process the resin is sucked through the reinforcement structure or preform by vacuum. The process uses an open mould and a vacuum bag and if large quantities are manufactured the vacuum bag can be replaced by a flexible counterpart for the mould.

4.3.1 RTM

Resin transfer moulding (RTM) is a technique where reinforcements or a preform are first applied to the mould, the mould is closed and the resin is injected to the mould with excess pressure. RTM technique is suitable for small or medium series production of parts with structural functions. A simple process description can be seen in Figure 26. RTM process is able to be fully automated.

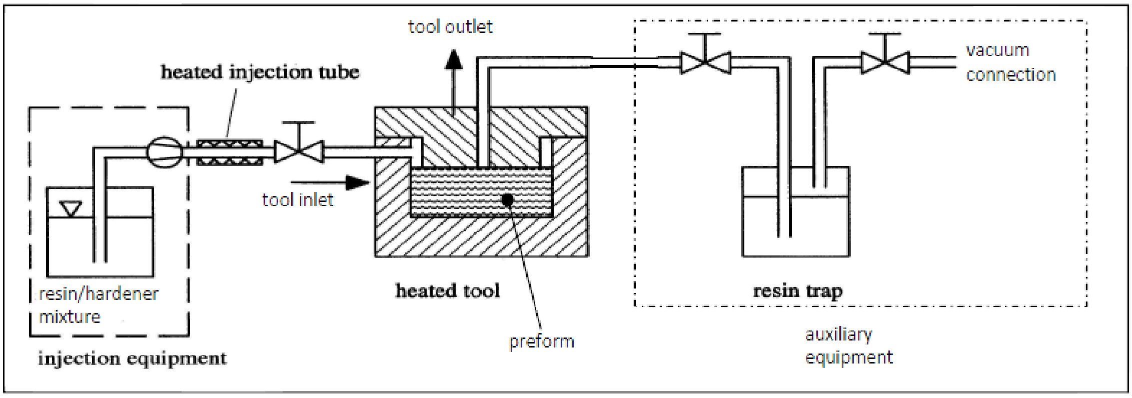


Figure 26. The RTM process [7].

As seen in Figure 26 the resin is first mixed in a container and then brought trough a heated injection tube to the heated mould containing the reinforcements. A resin trap seen in the picture is an additional item to the process.

For example Lamborghini and Ferrari among others are using the RTM. Lamborghini is building the chassis of the new Aventador with Lamborghinis own RTM process with thermoset Araldite resin [9]. Lamborghinis invention can be seen in Figure 27.

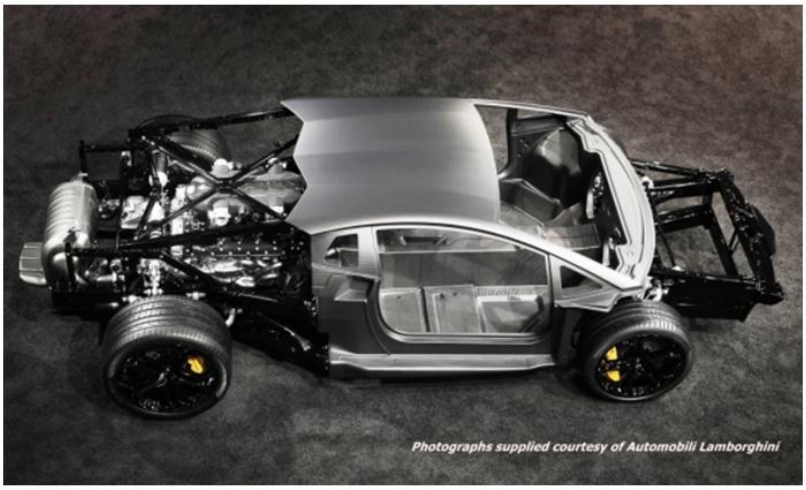


Figure 27. The Lamborghini Aventadors CF chassis using RTM [9].

As seen in Figure 27 the Lamborghini´s Aventador uses a combination of CFRP monocoque with steel tube framing in both ends of the vehicle to form a hybrid body structure.

The strengths of the RTM technique are as listed below:

- high percentage of reinforcements
- a variety of inserts can be used
- good tolerances
- relatively big parts can be manufactured
- parts can be structural or non-structural

An example of a part made with RTM can be seen in Figure 28.

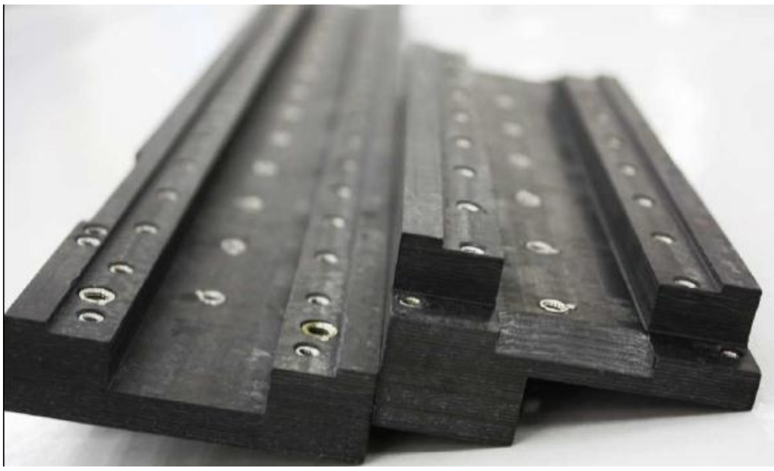


Figure 28. CFRP part made with RTM [7].

It can be seen in Figure 28 that a part made with RTM can incorporate multiple inserts to help joining the CFRP part to other parts.

Common RTM processes use epoxy, polyester and vinyl ester as resins whereas Bayer Material Science has recently developed a polyurethane resin to be used in the RTM process. It claims that the material is stronger and the cycle times faster among other benefits [26]. Also thermoplastics are currently researched and developed for use in the RTM process. One newcomer in the RTM field is epoxy structural reaction injection moulding (ESTRIM), announced to be faster and better method than RTM. ESTRIM uses epoxy as a resin.

4.3.2 RIM and its Variations

Reaction injection moulding (RIM) has been developed for PUR foamed plastics production. It normally uses two plastic components that are mixed in a mixer and then injected into a closed mould [1, p 175-176]. Due to advancement in PUR plastics it can also be used in applications where high heat resistance is required. The RIM processes are able to be automated.

RRIM uses chopped or milled fibres mixed in the plastic components. SRIM technique is quite similar to RTM since it uses the same kinds of reinforcing and moulding methods. A process description of RIM can be seen in Figure 29.

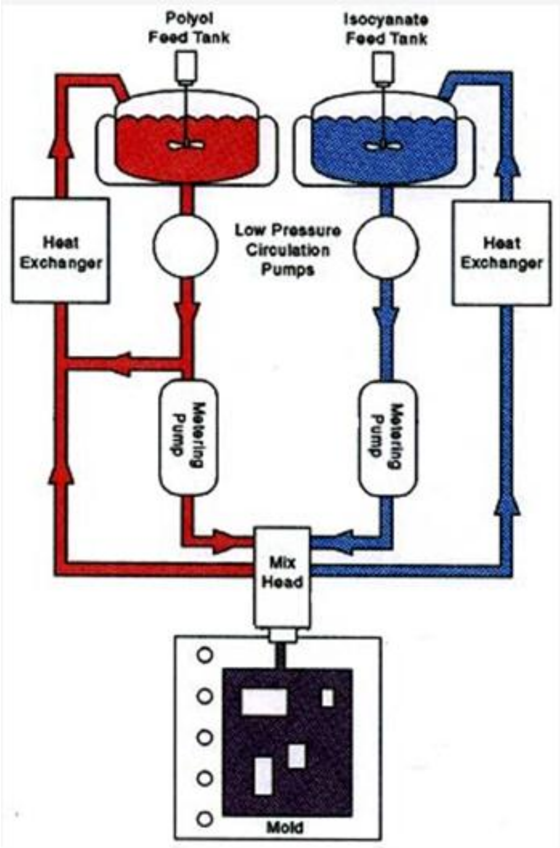


Figure 29. The RIM process [8].

The RIM equipment seen in Figure 29 consists of two separate tanks for raw materials, low pressure circulation pumps and metering pumps. Metering pumps push the raw materials to the mixing head and further to the mould.

RIM techniques are suitable for series production and are used for example in interior panels of trucks and personal transportation. RIM process doesn´t require high pressures since the raw materials are in a liquid state. Therefore also equipment can be lighter and cycle times faster. Since new polyurethanes are being developed, better attributes are gained in the future. The pros and cons of the RIM technique can be found in Table 19.

Pros	Cons
Fast cycle time Modest moulding pressure Dimensionally accurate and smooth surfaced parts Good flexibility attributes	Low modulus of elasticity and strength Fairly high investments in equipment In demanding surface finishes the part has to be painted

Table 19. Pros and cons of RIM technique. [1, p 176]

As seen in Table 19 the RIM technique provides with good quality parts in a short time but on the other hand does suffer from low internal rigidity and the need of additional finishing.

4.4 Extrusion and Pultrusion

In both techniques the outcome of the process is a continuous profile. Extrusion is mainly used for parts without the need for high mechanical requirements but in pultrusion the mechanical attributes can be very good since the reinforcing fibres are continuous. Some bended profiles can also be formed with pultrusion [1, p 186-189]. With pultrusion it is possible to make panel that can be combined to others to form a bigger structure. Pultrusion process can be seen in Figure 30.

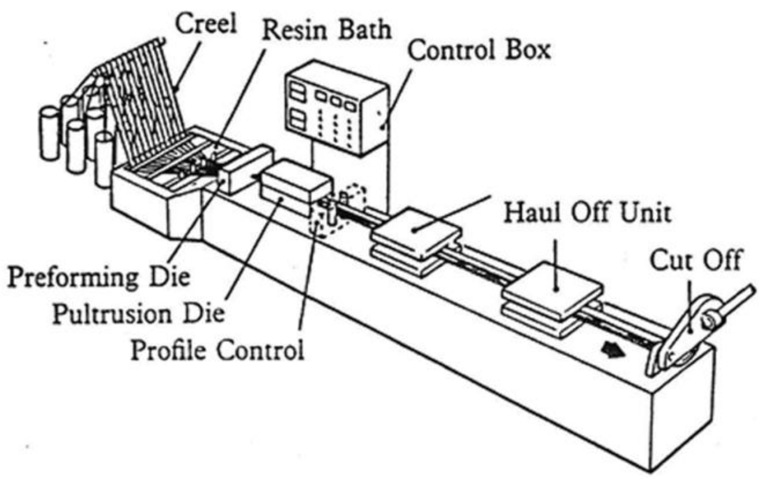


Figure 30. The pultrusion process [12].

As seen in Figure 31 the reinforcements come first from the creel and are then moistened with resin. After it they go through performing die and then continue to the pultrusion die. The pultrusion die is heated for curing purpose. A haul of unit pulls the product and it is being cut to a suitable length.

4.5 Production Series Definitions

The suitable manufacturing technique should be chosen according to the production series sizes. In directive 2007/46/EC annex VII the small series production of M1 class vehicles is defined to be 1000 a year. Other series quantities are defined by manufacturers and they vary among them. Table 20 includes figures of different production series.

Series type	Annual quantity
Single / concept vehicles	1-2
Prototype vehicles	10-50
Small series	≤1000
Series production	>1000

Table 20. Definitions of production series.

The series sizes presented in Table 20 are suggestive and may vary among manufacturers whereas the annual production limit for small series production is set to 1000 vehicles by EU legislation.

4.6 Comparison of Techniques

This chapter provides a variety of technical and economical comparisons. In order to choose the most suitable manufacturing technique a summary can be found in Table 21.

	Cost-effective series size	**Mould time**	**Strength class**	**Typical reinforcement-%**	**Direction of reinforcing**	**Surface quality**
Wet lay-up	1-1000	5 min- 24h	Average	20-40	As desired, even	Excellent
RTM	1000-2000	10-20 min	Average	15-30	Even	Excellent
SMC	1000-100000	30 s- 3 min	Low – Average	15-35	Even	Good
RRIM	1500-100000	1-2 min	Low	5-25	Even, in direction of resin flow	Excellent
Pultrusion	1000 m-10000 m	Continuous	High	30-75	Directed	Average

Table 21. Technical and economical comparison of techniques (1, p 192-193).

The techniques in Table 21 are used in manufacturing panel–like structures though pultrusion is mainly used for hollow profiles but is researched for making panels as well.

4.7 Techniques Applied by Valmet-Automotive

The capabilities of Valmet-automotive to produce CFRP parts for automotive exterior applications are shown in Appendix 6.

5 Refining

The correct refining technique should be chosen according to the required finishing quality. The OEM will inform on how to make the right choice by providing the instructions.

5.1 Paint

Painting composite parts is different than painting conventional steel or aluminium parts. It must be noted that the surface of a composite part is more likely to be rough than in the metal parts. Also the heat endurance and the thermal expansion attributes differ from sheet metal parts. It means that either the curing temperature of the paint should be low enough or the heat endurance of the plastic high enough to make it possible to paint the composite parts using the same painting procedure as with the metallic parts. In automotive painting process the parts can be painted separately and added to the BIW in-line or if required, off-line [18, p 31, 36-39].

In automotive industry a three zone method is commonly used for defining the different surface quality zones of the products. An example can be seen in Figure 31.

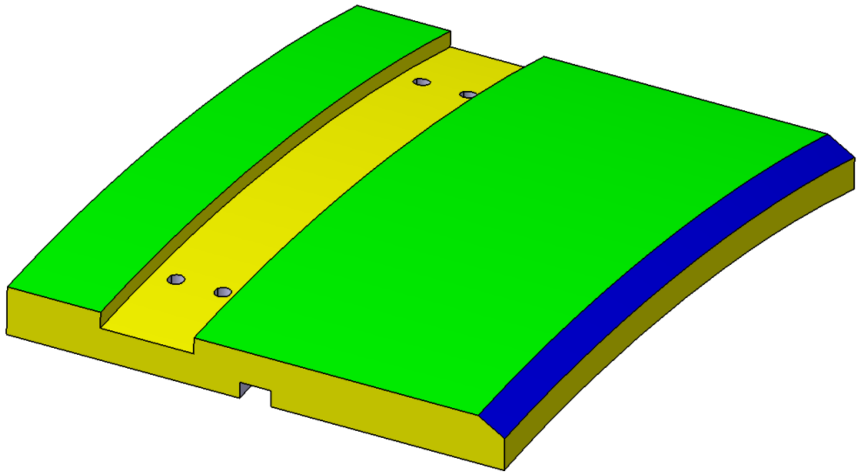


Figure 31. Example of 3D-model with the different zones indicated with different colours.

The different zones in Figure 31 are as follows: the first zone (green) indicates surface of the part where there shall not be any kinds of defects, often called class A surface. The second zone (yellow) indicates the surfaces where there can be minor defects, also referred as a class B surface. The third zone (blue) indicates the surfaces that are hidden or are very rarely or briefly seen, also commonly known as class C surface.

CFRP parts should not only withstand the environmental temperature and humidity conditions but also the circumstances in the painting process. That is why choosing the right stage for the CFRP part is to be attached to the body frame is essential [18, p 31-32]. A chart of temperatures and process stages can be found in Figure 32.

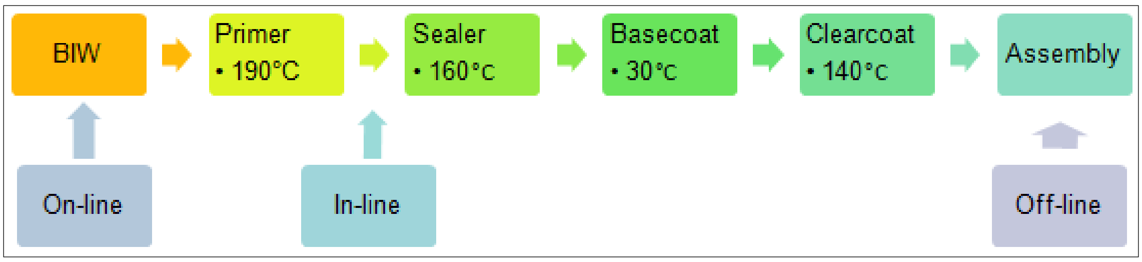


Figure 32. Painting process with different phases where FRP parts can be applied to the BIW [18, p 31].

As seen in Figure 32 the painting process itself sets some boundaries for selecting a suitable matrix plastic. As for Valmet-Automotive the painting process schematic can be seen in appendix 5. Although the plastic might endure the heat in the process, the CTE differences between the BIW and the FRP parts have to be noted when it comes to attaching the parts. The following chart in Figure 33 provides with a rough summary on the matter.

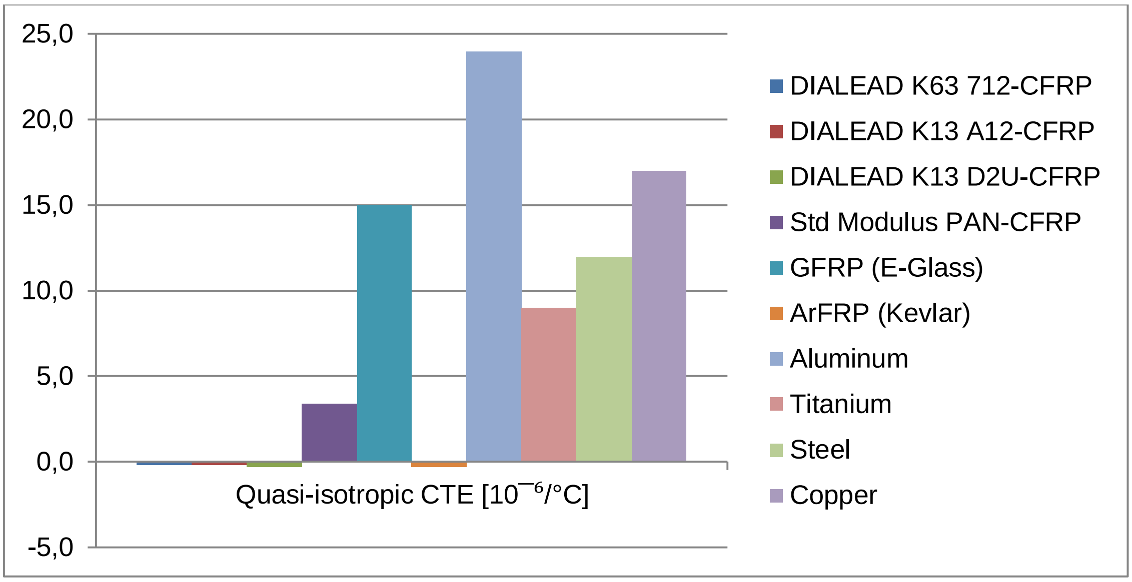


Figure 33. Comparison of CTEs for some typical FRP and metallic parts [13].

As seen in Figure 33 the differences between CTEs between CFRPs and metals are significant and thus need to be taken into consideration when the parts are joined together and also the read-thru effect of reinforcements caused by differences in CTE between the matrix and the reinforcements must be noted.

5.2 Gelcoat and Topcoat

Gelcoat is commonly a pigmented resin based coating material that is applied to the mould in the liquid state. It is primarily used as a surface layer that is a durable and protective which at the same time provides the part with good quality surface. Top coat is also a resin-based coating material but unlike gelcoat it is usually transparent. Both coatings are commonly equipped with thixotropy agents and normally cure faster than the actual laminate whilst becoming an integral part of the laminated product.

6 Quality

In order to produce high quality parts out of CFRP the common quality-related aspects need to be familiarised. The quality of a CFRP part is mainly influenced by the materials and manufacturing technique used whereas in hand lay-up techniques it is mostly the skill of the workers that has the biggest effect on the resulting parts quality. In exterior parts the main requirements are in the fields of surface quality, appearance, and temperature and humidity resistance while they also have to withstand stone impacts, and scratches etc. [48].

The most important tolerances are typically set for geometry and attachment related surfaces and holes etc. as well as for surface quality. Usually geometry tolerances are stricter in the parts edges than in the planar surfaces, which is because parts usually have to have similar curvatures on the edges to that of the parts next to them. The tolerances that can be achievable are resulting from the materials and technique used as well as from the skill of the workers and they are usually set according to the application.

6.1 Surface Quality

The surface quality of a part is essential in case of exterior parts since they are mostly visible. As mentioned in Chapter 5.1 when it comes to painting a part the surfaces are divided into separate quality zones that in turn affect the requirements placed for the part structure and the related manufacturing process. The manufacturing process parameters along with the materials used play a significant role on the resulting surface quality as well as in the other aspects of the part. An example of surface defects and their allowances on different surface zones can be seen in Table 22.

Defect	**Zone**		
	1 (Class A)	**2 (Class B)**	**3 (Class C)**
Resin accumulation	Not Allowed	Allowed	Allowed
Distortion of Fabric	Not Allowed	Not Allowed	Allowed
Porosity	Not Allowed	Not Allowed	Allowed
Colour Mismatch	Not Allowed	Not Allowed	Not Allowed

Table 22. Examples of surface defects and their allowances in an unpainted CFRP part.

The examples presented in Table 22 are only examples and not applicable in general since the quality requirements are always manufacturer and case specific. More thorough examples of surface defects are presented in Appendix 7.

6.2 Testing

Testing procedures are commonly divided into two types that are non-destructive (NDT) and destructive. In case of surface quality and geometry testing the NDT methods are the most suitable since they do not cause any defects on the parts and thus the part can afterwards be used in its intended manner. The testing requirements vary among manufacturers whereas the testing processes are usually standardised. As an example General Motors has its own standard document (GMW14650) where performance requirements for exterior parts made of plastics are covered. The testing procedure standards are from ISO, SAE and ASTM.

The appearance of a part can be tested in the simplest way by examining the part by viewing it and thereby form an overall impression. There are also ways of testing the appearance features such as gloss and colour by scientific means. Specification DIN EN ISO 2813 defines the ways of inspecting gloss of a painted or coated part whereas colour is measured according to DIN 6175. An example of gloss measuring device can be seen in Figure 34.

Figure 34. Gloss measuring device [49].

The gloss measuring device in Figure 34 is a hand held one from Zehntner an it is suitable for measuring gloss from mat to high gloss surfaces.

In colour testing spectrophotometer is used to determine whether the part has the right colour or not. An example of a spectrophotometer can be seen in Figure 35.

Figure 35. Spectrophotometer MA68II [50].

The spectrophotometer seen in Figure 35 is designed for measuring metallic and pearlescent paints and is manufactured by X-Rite.

Smoothness of a parts surface can be tested visually or with scanning equipment such as seen in Figure 36.

Figure 36. Surface quality measurement tool by BYK (51).

The tool seen in Figure 36 is used for detecting roughness and gloss on a painted surface.

7 Safety and Environment

Working with and manufacturing CFRP parts include some special matters to be considered. Most important safety instructions and environmental matters are discussed in this chapter. Also a list of information sources can be found in section 7.3.

Most of the resins and solvents used in the composites manufacturing process are flammable. Therefore when it comes to storing and handling, appropriate procedures should be carried out based on local instructions on the matter.

One important matter to be considered is the electrical conductivity of the carbon fibre dust particles. When the dust comes to contact with low voltage devices such as computers, it can cause the device to short circuit or get damaged otherwise.

7.1 Working Conditions

The most important safety matters are the working conditions. The instructions for correct working conditions can be found in the safety instructions provided by the occupational healthcare department. The recommended ways to work with materials can be found in the material safety data sheet provided by material supplier. The safety data sheet should always be available. An example of safety data sheet can be found in the appendices.

7.2 Basic Safety Equipment

Safety equipment should be used according to the prevailing circumstances. Usually it is recommended to use at least some suitable plastic gloves when handling resins and other chemicals in the process. Using gloves also prevents the grease from the skin from contaminating surfaces.

It is also advisable to use suitable respiratory protective equipment whenever one is tooling the composite parts since there will be great amounts of dust in the air during the tooling process. Carbon fibre dust can cause lung diseases. Always when working with chemicals, correct protective equipment should be used.

The fumes from resins and solvents as well as carbon fibre dust can be irritating or harmful. Especially when using the hand lay-up technique it must be ensured that there is sufficient airflow in the place of work. Local ventilation or suction would be the best ways of preventing the fumes or dust to spread around the working place.

7.3 Where to Look for Instructions

In case of Valmet-Automotive the required safety instructions can be found for example in following places:

- Occupational health care
- PLAZA
- Lotus Notes: Management system – OHS – Operational Instructions – T4.4
- WebKTT (access through supervisor)
- HSE – monitor (reports on accidents and safety risks)
- Safety data sheet (provided by material supplier)

7.4 Recycling and Reuse of Materials

As there is a growing number of manufacturers using CFRP parts in their cars the environmental issues such as recyclability and reuse of materials are becoming more important. For example the since 2006 End-of-Life Vehicle Directive requires that 85 % of all manufactured vehicles must be recyclable when disposed. After 2015 the directive requires an even higher recyclable content of 95 % in every manufactured vehicle.

There are separate ways for recycling and reuse whether it is thermosetting or thermoplastics-based CFRP that is to be disposed. The thermosetting plastic –based CFRP waste can be processed in mechanical or thermal processes. The processes for recycling thermoset composites can be seen in Figure 37.

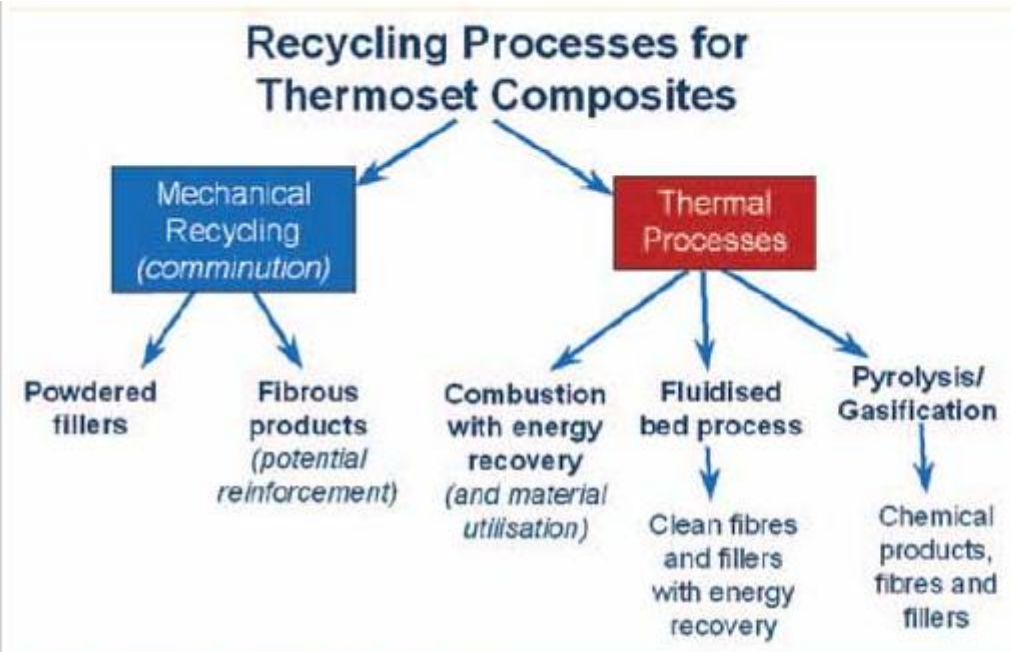


Figure 37. Recycling processes for thermoset composites [47].

As seen in Figure 37 the recycling processes for thermosetting plastic –based composite waste produce several reusable output such as fillers, fibrous products, clean fibres and chemical products. In some processes energy recovery is possible and thus improves the energy economy of the recycling.

The thermoplastic based composites are much easier to recycle since the plastic can be melted and thus separated from the reinforcements and both of the components can be reused to produce new parts.

8 Conclusions

The goal of this study in the first place was to provide Valmet-Automotive Ltd (VA). a guidebook for manufacturing CFRP parts for automotive exterior applications and to carry it out as thoroughly as possible in the given time frame. It was soon that the field of the study was so wide that it had to be narrowed down just to incorporate basic guidelines and principles of the manufacturing techniques and materials suitable for and the most common in the exterior part applications. Due to difficulties in getting cost related information from suppliers, a thorough economical comparison of the techniques was not possible to be included in the guidebook. It would have been extremely useful in choosing the right manufacturing technique. It was also discovered during the study that since carbon fibre is such a new material in Finland even the Finnish Institute of Occupational Health (FIOH) has not yet done any research on the effects that the carbon fibre could have on the health of the people working with it.

The resulting guidebook is much more like a book on how to get started with the CFRP manufacturing than a hand book containing thorough process descriptions of the techniques and materials so that someone could actually start manufacturing parts. It was carried out successfully in the given timeframe to meet the VAs demand for a guidebook of CFRP and in addition VA gained precious information of its own capabilities and thus requirements regarding CFRP parts manufacturing. The study also pointed out what needs to be purchased in order for the company to manage in the field of CFRP manufacturing.

In the future it will be essential to keep this guidebook up to date since the CFRP related techniques and materials are developed continuously. It would also be useful to produce more thorough guidebooks on the manufacturing techniques to further help in choosing the right technique for manufacturing parts. A cost related survey should be also carried out that would incorporate the pricing of parts and capabilities of different kinds of manufacturing techniques to produce them in an economical way.

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50 X-Rite MA68II User Manual, X-Rite Ltd. 2010. Internet Document. Read 17.08.2012. (http://www.xrite.com/documents/manuals/en/MA68b-500_MA68B_Users_Manual_en.pdf)

51 Instruments for Orange Peel and DOI metering, BYK 2012. Internet Document. Read 17.08.2012. (https://www.byk.com/en/instruments/products/?a=1&b=14&f=25&faction=)

Material Safety Data Sheet – Toho Tenax

Toho Tenax
Toho Tenax America, Inc.

TEIJIN

MATERIAL SAFETY DATA SHEET

MSDS NO. 0501 Rev E

CHEMTREC EMERGENCY TELEPHONE NO. (800) 424-9300   EFFECTIVE DATE: March 23, 2011

TOHO TENAX AMERICA, INC.
121 Cardiff Valley Road, Rockwood, TN 37854 USA
TENAX® CONTINUOUS, CHOPPED OR MILLED CARBON FIBERS

1. IDENTIFICATION OF THE SUBSTANCE / PREPARATION AND OF THE COMPANY

Product: Tenax®-A continuous, chopped or Milled carbon fibers with NO sizing (surface finish)

Registration number: Not applicable
Use: None specified
Identified use: None specified
Method of operation: See product information.

Company: Toho Tenax America, Inc.
121 Cardiff Valley Road
Rockwood, TN 37854

Phone: (865) 354-4120
Fax: (865) 354-8409
Homepage: www.tohotenaxamerica.com
Contacts:
Jason Carling – Global R&D Manager jcarling@tohotenax-us.com
Mark Klemmer – ES&H Manager mklemmer@tohotenax-us.com

2. HAZARDS IDENTIFICATION

Physical / Chemical Hazards: See Section 10.
In the supplied form the product is not explosive at all, however the build-up of fine dust can lead to a risk of dust explosions.
Human health dangers: See Section 11.
Environmental hazards: No specific hazards known.
Other hazards: None
Hazard symbols: None
R-phrases: None

3. COMPOSITION / INFORMATION ON INGREDIENTS

CAS: 7440-44-0   Carbon Fiber (derived from polyacrylonitrile) ~100%

Comment on component parts: No dangerous components.

4. FIRST AID MEASURES

General information: Not applicable
Inhalation: Ensure supply of fresh air.
Skin contact: Supply with medical care. Consult a doctor if skin irritation persists.
Eye contact: In case of contact with eyes rinse thoroughly with plenty of water and seek medical advice.
Ingestion: Supply with medical care. Rinse out mouth and give plenty of water to drink. Induce the patient to vomit of his own accord only if fully conscious.
Advice to doctor: Treat symptomatically

5. FIRE FIGHTING MEASURES

Suitable extinguishing media: Foam, dry powder, water spray jet, carbon dioxide
Extinguishing media that must not be used: Full water jet
Special exposure hazards arising from the substance or preparation itself or combustion products: Carbon monoxide (CO) Nitrogen oxides (NOx).
Explosion: Avoid generating dust; fine dust dispersed in air in sufficient concentrations, and in the presence of an ignition source is a potential dust explosion hazard.
Special protective equipment for firefighters: Do not inhale explosion and/or combustion gases. Use self-contained breathing apparatus.
Additional information: Fire residues and contaminated firefighting water must be disposed of in accordance within the local regulations.

6. ACCIDENTAL RELEASE MEASURES

Personal precautions: Not applicable
Environmental precautions: Dust deposits should not be allowed to accumulate on surfaces as they may form an explosive mixture if they are released into the atomshpere in sufficient concentrations during processing. Avoid dust generation during processing, ie cleaning of surfaces with compressed air.
Methods for cleaning up: Take up mechanically. Dispose of absorbed material in accordance within the regulations.

7. HANDLING AND STORAGE

Advice on safe handling: No special measures necessary if used correctly.
Advice on protection against fire and explosion: Dust can form an explosive mixture with air. Keep away from sources of ignition. Dust deposits should not be allowed to accumulate on surfaces as they may form an explosive mixture if they are released into the atomshpere in sufficient concentrations during processing. Avoid dust generation during processing, ie cleaning of surfaces with compressed air.
- refrain from smoking. Hazard analysis should be completed to identify the need for process precautions related electrical bonding and grounding.
Requirements for storage rooms and vessels: No special measures necessary.
Advice on storage compatibility: Do not store together with oxidizing agents.
Further information on storage conditions: Store in a dry place, recommended storage temperature: < 50 °C, relative humidity: < 85 %

8. EXPOSURE CONTROLS / PERSONAL PROTECTION

Additional advice on system design: Ensure adequate ventilation on workstation. If dust handling systems are used they should be designed in a manner to prevent the escape of dust into the work area.
Ingredients with occupational exposure limits to be monitored: 0.5mg/m**, General remarks: fibers/ml (respirable fibers). Carbon fiber on basis polyacrylonitrile (Carbon) > 95%. *LTEL: Long-term exposure limit
Respiratory protection: Breathing apparatus in the event of high concentrations. short term: filter apparatus, filter N95. Dust may produce mechanical irritation to the mucus membranes of the nose, throat and upper respiratory tract.
Hand protection: Butyl rubber, > 120 min (EN 374)
Eye protection: Safety glasses
Skin protection: Mechanical irritation accompaniecd by itching or dermal effects may occur from exposure to material. Clean room type clothing that are a light weight fabric and is well ventilated and prevents the transfer of dust. Consider taping at the wrist and ankle areas to control contact with exposed areas. PPE hazard analysis based on user process should be completed.
General protective measures: Avoid contact with eyes. Do not inhale dust.
Hygiene measures: Wash hands before breaks and after work. Use barrier skin cream.
Delimitation and monitoring of the environmental exposition: Not determined

9. PHYSICAL AND CHEMICAL PROPERTIES

Form: Fiber
Color: Black
Odor: Odorless
pH-value [1%]: Not applicable
pH-value: Not applicable
Boiling point [°C]: Not applicable
Flash point [°C]: Not applicable
Flammability [°C]: Not applicable
Lower explosion limit: Not applicable
Upper explosion limit: Not applicable
Oxidizing properties: No
Vapour pressure [kPa]: Not applicable
Density at [°C]: 20
Density [g/ml]: 1.7 – 1.90 (carbon density)
Bulk density [kg/m³]: Not applicable
Solubility in water: Insoluble
Partition coefficient [n-octanol/water]: Not applicable
Viscosity: Not applicable
Relative vapor density determined in air: Not applicable
Evaporation speed: Not applicable
Melting point [°C]: ca. 3500
Autoignition temperature: Not applicable
Decomposition temperature: > 650 (in air), **preparation** > 290
Electrically Conductivity: Yes

10. STABILITY AND REACTIVITY

Hazardous reactions: Reactions with strong oxidizing agents. Accumulation of fine dust may entail the risk of a dust explosion in the presence of air.
Hazardous decomposition products: No hazardous decomposition products will be formed during normal useage of carbon fiber. Complete or partial combustion of the surface coating on "sized" carbon fiber may generate COx, NOx, and / or other trace chemicals.

11. TOXICOLOGICAL INFORMATION

Acute oral toxicity: not determined
Acute dermal toxicity: not determined
Acute inhalational toxicity: not determined
Irritant effect on eye: not determined
Irritant effect on skin: not determined
Sensitization: not determined
Subacute toxicity: not determined
Chronic toxicity: not determined
Mutagenicity: not determined
Reproduction toxicity: not determined
Carcinogenicity: not determined
Experiences made in practice: Fiber abrasion can cause mechanical skin irritation.

12. ECOLOGICAL INFORMATION

Fish toxicity: Not applicable
Daphnia toxicity: Not applicable
Behavior in environment compartments: not determined
Behavior in sewage plant: Not applicable
Bacteria toxicity: not determined
Biological degradability: Not applicable
COD: not determined
BOD 5: not determined
AOX-advice: No dangerous components.
General information: Ecological data are not available.

13. DISPOSAL CONSIDERATIONS

Product: For recycling, consult manufacturer.
For recycling, consult waste disposal centers.

Contaminated packaging: Packaging that cannot be cleaned should be disposed of as for product.
Uncontaminated packaging may be taken for recycling.

14. TRANSPORT INFORMATION

Classification according to DOT: Non-hazardous
- **Classification Code:**
- **Label:**
- **ADR Limited Quantities:**

Classification according to IMDG: Not classified as "Dangerous Goods" - -
- **EMS:**
- **Label:**
- **IMDG Limited Quantities:**

Classification according to IATA: Not classified as "Dangerous Goods"
- **Label:**

15. REGULATORY INFORMATION

Exposure Risk: Not determined
Chemical safety report: Not determined
Labeling: All chemicals in this product are included on the TSCA Inventory
Hazard symbols: None
R-phrases: None
S-phrases: None
Special labeling:
Authorization, TITLE VII: Not applicable
Restrictions, TITLE VIII: Not applicable
TRANSPORT REGULATIONS: IATA-DGR (2008).

16. OTHER INFORMATION

Observe employment restrictions for people: No
VOC (1999/13/CE): Not applicable

Ampreg 22 Resin System User Guide

Ampreg 22
Epoxy Laminating System

- Optimised for open-mould laminating of large structures
- Improved health and safety
- Germanischer Lloyd approved*

Introduction

Ampreg 22 is an established and widely used laminating system. It is intended for both wet lay-up and vacuum bagging processes and uses the most up-to-date epoxy chemistry available. Its long working time, low exotherm and low viscosity make it ideal for the manufacture of large, high performance composite structures.

The Ampreg 22 system consists of a resin and a choice of five hardeners to provide a complete range of working properties. With its 14 hour hardener Ampreg 22 can provide laminate working times of over 14 hours at 20°C whilst having low exothermic reactions even when used in thick sections. The Fast hardener has such rapid through-cure at 25-30°C that it can be used to produce small mouldings that are demouldable in just a few hours.

The low initial viscosity allows laminates to be produced by contact pressure, vacuum or pressure bag techniques, filament winding, or vacuum assisted resin injection. Thorough wetting of reinforcement fibres is ensured by the low viscosity and excellent air release properties of the resin / hardener mixture. This, in particular, assists with the impregnation of aramid and carbon fibres.

Ampreg 22 resin is coloured bright yellow, with the hardeners having a range of different colours. This makes component identification easier and facilitates thorough mixing of resin and hardener. For example, the Extra Slow Hardener is coloured blue leading to a clearly identifiable green colour when thoroughly mixed with the resin.

Ampreg 22 resin has one of the lowest diluent contents of any epoxy resin system available today. Together with the use of some unique chemistry in the hardeners, the overall system shows marked improvements in handling safety over other products. The system is formulated without DDM, which is particularly important for those using the product in open-mould, hand lay-up situations, where skin contact and exposure to vapours can be difficult to avoid completely.

*High Tg Hardener excluded

Instructions for Use

Workshop Conditions
Ampreg 22 is optimised for use between 18 - 25°C. At lower temperatures the product thickens and may become unworkable. At higher temperatures working times will be significantly reduced. Maximum relative humidity for use is 70%.

Mixing and Handling
Ampreg 22 resin is combined with either Ampreg 22 Fast, Standard, Slow, Extra-Slow or 14 Hour hardener in the following ratio:

Ampreg 22 resin : Ampreg 22 hardener
100 : 28 (by weight) All hardeners
100 : 32 (by volume) Fast
100 : 33 (by volume) Standard or Slow
100 : 34 (by volume) Extra Slow or 14 Hour
100 : 29 (by volume) High Tg

It is important that the resin and hardener components are measured out accurately. Measurement by weight and electronic scales are recommended for this purpose. The resin / hardener mixture should be well mixed, paying particular attention to the sides and bottom of the mixing vessel. The mixture should then be transferred to a shallow tray in order to reduce the exothermic heat build up, which would reduce pot life and working time. Accurate measurement of the components and thorough mixing are essential. Deviating from the prescribed mix ratio will not accelerate or inhibit the cure and can seriously degrade the properties of the system.

Ampreg 22 resin and hardeners are pigmented as a visual aid for the user - see component properties table. The colours are primarily a quick and easy guide to help distinguish the resin and different hardener speeds in the workshop. In addition, when mixing the chosen hardener with the resin, its colour blends with the yellow colour of the resin to help indicate that the two components have been mixed.

Ampreg 22 resin and hardeners will lose their colour tint strength with time. This is a natural function of the pigments used and does not affect the product performance. In the case of Ampreg 22 Slow Hardener and Ampreg 22 Resin, the pigment can settle to the bottom of the container with time - if this should happen they may be returned to their original uniform colour by stirring before use.

Mould Release
From smooth metal or grp moulds tests have shown that suitable release can be obtained by use of 5-6 waxings of a carnauba based wax e.g. Polywax. Use PVA for less well prepared or complex surfaces. Whichever mould release is proposed it is recommended that a test laminate is laid up in the mould to be used, with the mould release proposed, in order to ensure an adequate and effective part release. Semi permanent agents such as Frecote or Chemlease are also suitable.

Application
The mixed system is usually applied by foam roller from a roller tray (which also serves to increase exothermic heat release, as described above). High and accurate fibre volume fractions can be obtained by applying known weight of mixed resin / hardener to each fabric / fibre layer. As a general rule of thumb, resin weight per square metre must be no more than, and preferably less than, the area weight of the fabric being wet out. If the laminate is particularly thick, it is recommended that slower hardeners are used for the first layers put down and faster hardeners in the later layers. In this way the whole thickness laid down remains workable for approximately the same time.

Pregel
Ampreg Pregel is a thixotropic resin which, when used with the appropriate hardener, can be added to, or used in place of, Ampreg 22 resin/hardener mixes. Mix Ampreg Pregel resin with any of the Ampreg 22 Hardeners at the ratio indicated in the Ampreg Pregel datasheet. Mixed Ampreg Pregel / Ampreg 22 Hardener can be added to an Ampreg 22 resin/hardener mix to make it more thixotropic. A separate data sheet is available describing this product's use in more detail.

- As a resin modifier to reduce drainage in laminates.
- As an adhesive mix for bonding core materials to Ampreg 22 laminate skins.
- For the secondary bonding of pre-formed Ampreg 22 laminate components.

Bonding Techniques & Peel Ply
Where it is necessary for a bonding operation to be carried out following the cure of the Ampreg 22 laminate, a suitable Peel Ply can be applied to the surface to be bonded during the lay-up process. After curing and just prior to bonding, the Peel Ply is stripped off leaving a clean, dust and grease free surface, with an already 'textured' surface which makes the 'keying' process less time consuming.

Peel Ply is used on laminate surfaces which need to be left to cure or partially cure before further laminating or bonding operations. The peel ply serves two functions - preventing the surface from becoming contaminated and / or damaged, and providing a 'textured' surface that can reduce the level of preparation required for the secondary laminating of bonding operations.

SP-High Modulus recommends the use of its Stitch Ply A peel ply, or suitable alternative product. Any proposed peel ply should be tested prior to use to ensure that it not only releases adequately from the laminated surface but also does not leave any residues behind which may impair adhesion. If in doubt please contact Technical Services.

Vacuum Bag Techniques

Consolidation of the laminate can be obtained either by hand using paddle rollers or by vacuum or pressure bags. A typical vacuum bag arrangement is shown in figure 1. It is important when using high vacuums and using the slower hardeners that vacuum is not applied until at least 50% into the laminate working time, as excessive flow and resin starved laminates may result (see working properties). Heating can be economically and effectively achieved with either space heaters under an insulation tent or heated blankets with insulation over. If vacuum is applied earlier only 30-50% vacuum should be used. Details of the various types of system are available from Technical Services.

Ampreg 22 resin with either Slow or Extra Slow hardener is best suited. Do not expose wet laminates to excessive vacuum pressures - keep below 0.8 bar (80% vacuum). Gurit supplies a range of Tygavac vacuum bag materials and ancillaries. For details of effective vacuum bag consolidation, please contact Technical Services.

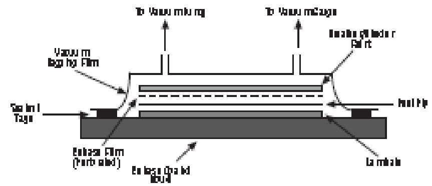

Figure 1

Core Materials

SP-High Modulus supplies Corecell™ SAN closed cell foam for sandwich laminate construction. Other core materials such as PVC foam, Nomex honeycomb and end grain balsa, are also suitable for use with Ampreg 22 system. For further information on the use of core materials with Ampreg 22 system, please contact Technical Services.

Curing Schedule

Ambient Temperature Cure

The system has been developed to return good mechanical properties after cure at ambient temperatures, the minimum recommended temperature being 18°C, and excellent properties after a slightly elevated temperature post-cure. An initial cure of at least 48 hours (with slow and extra slow hardener) or 16 hours (with fast or standard hardener) at 18°C is recommended before demoulding. Laminates moulded with Fast, Standard or Slow hardener and subjected to an ambient temperature cure should be allowed 14 days before the system can be considered to be adequately cured (see working properties). Such mouldings should be kept in a warm dry environment during this period. When using the Slow, Extra Slow and High Tg Hardeners exclusively, an elevated temperature cure is strongly recommended. Ideally the postcure should be undertaken prior to demoulding. When using the 14 Hour hardener the laminates must be cured at a temperature of at least 55°C.

Elevated Temperature Cure

Post curing the laminate will greatly increase mechanical properties. The system will achieve similar properties with a cure of 5 hours at 70-80°C or 16 hours at 50°C (with the exception of the 14 hour hardener which needs a minimum of 16 hours @ 55°C postcure). The latter temperature is easily achievable with low cost heating and insulation techniques. The tables in the datasheet show that these cure cycles improve the properties considerably.

The post cure need not be carried out immediately after laminating. It is possible to assemble several composite components and post-cure the entire assembly together. It is recommended, however, that elevated temperature curing should be completed before any further painting / finishing operations. Furthermore, care should be taken to adequately support the laminate if it is to be post cured after demoulding, and the laminate must be allowed to cool before the support is removed.

Properties

Component Properties							
	Resin	Hardener					
		Fast	Std.	Slow	Extra Slow	14 Hour	High Tg
Mix Ratio (by weight)	100	28	28	28	28	28	28
Mix Ratio (by volume)	100	32	33	33	34	34	29
Viscosity @ 15°C (cP)	9270	420	67	43	34	48	110
Viscosity @ 20°C (cP)	3915	270	40	36	22	36	80
Viscosity @ 25°C (cP)	2396	164	24	28	14	30	60
Viscosity @ 30°C (cP)	1312	105	15	21	9	21	40
Shelf Life (months)	24	24	24	24	24	24	24
Colour	yellow	(6)*	red	green	blue	blue	*6
Mixed Colour	-	yellow	pink	green	green	green	yellow
Component Dens. (g/cm³)	1.147	0.958	0.950	0.947	0.940	0.944	0.96
Mixed Density (g/cm³)	-	1.108	1.101	1.099	1.097	1.094	1.10
Hazard Definition	Please refer to MSDS information.						

*Hardener is not pigmented - Gardener colour stated.

Working Properties	Resin / Fast Hardener				Resin / Standard Hardener				Resin / Slow Hardener				Resin / Extra Slow Hardener				Resin / 14 Hour Hardener				Resin / High Tg Hardener
	15°C	20°C	25°C	30°C	15°C	20°C	25°C	30°C	15°C	20°C	25°C	30°C	15°C	20°C	25°C	30°C	15°C	20°C	25°C	30°C	20°C
Initial Mixed Viscosity (cP)	4132	1995	1265	881	2848	1529	805	431	1610	950	579	361	1402	722	461	294	1288	855	577	378	1110
†Gel Time - 150g Mix in water (hrs:mins)	0:31	0:26	0:22	0:18	2:18	1:31	1:00	0:40	9:10	5:44	3:35	2:12	14:00	9:10	7:00	4:50	15:00	11:40	09:30	07:30	5:40
†Pot Life - 500g Mix in air (hrs:mins)	-	0:25	-	0:15	-	0:26	-	0:20	-	2:12	-	1:10	-	5:35	-	2:00	-	14:30	-	5:40	2:20
†Earliest Time To Apply Vacuum (hrs:mins)	1:30	1:10	1:00	0:50	2:00	1:50	1:30	1:20	5:30	4:40	4:00	3:20	8:40	7:00	5:50	4:45	14:10	12:10	10:30	8:20	4:40
†Latest Time To Apply Vacuum (hrs:mins)	3:10	2:15	1:40	1:10	3:20	2:45	2:20	2:00	7:45	6:40	5:30	4:20	11:30	9:10	7:20	5:50	19:35	16:00	12:40	10:40	6:40
†Earliest Time To Turn Off Vacuum (hrs:mins)	5:00	3:30	2:30	1:40	5:00	4:00	3:15	2:40	18:30	15:30	12:30	9:30	48:00	30:00	18:00	11:20	*	*	*	*	15:30
†Demould Time (hrs:mins)	6:00	4:00	3:00	2:00	8:20	5:20	4:00	3:00	36:00	30:00	25:00	19:00	100:00	62:00	37:00	22:00	*	*	*	*	30:00

NOTES: *Ampreg 22 with 14 Hour hardener will ideally be post cured before de-moulding. Earliest time to turn off vacuum and demould time are totally dependent on the intended post cure schedule. Please refer to Technical Services for further information on this point.

For an explanation of test methods used see 'Formulated Products Technical Characteristics'. Please refer to the "Intro to Form Prds".pdf, which can be found in the Formulated product section on the website. www.gurit.com

All figures quoted are indicative of the properties of the product concerned. Some batch to batch variation may occur.

†All times are measured from when resin and hardener are first mixed together

Properties (cont'd)

Cured System Properties	Room Temperature Cure (28 days @ 21°C)				Post Cured (24 hours @ 21°C + 16 hours @ 50°C)					
	Fast	Std.	Slow	Extra Slow*	Fast	Std.	Slow	Extra Slow	14 Hour**	High Tg
Tg DMTA (Peak Tan δ)(°C)	71.5	70.9	71.1	60.8	91.6	78.8	83.6	82.2	70.8	-
Tg Ult - DMTA (°C)	102.7	106.4	108.7	110.3	102.7	106.4	108.7	110.3	94.9	115
ΔH - DSC (J/g)	50	44	65	59	13	0	15	27	0	0
Tg1 - DMTA (°C)	61.5	58.3	63.2	50.4	79.7	73.6	73.6	72.7	60.7	77
Est. HDT (°C)	57	56	56	46	77	64	69	67	56	73
Moisture Absorption (%)	2.31	2.25	1.41	1.46	1.92	-	0.62	1.22	-	1.1
Cured Density (g/cm³)	1.16	1.13	1.14	1.14	1.16	1.14	1.14	1.14	1.14	1.14
Linear Shrinkage (%)	1.7	1.4	1.6	1.7	1.7	1.5	1.5	1.6	1.6	1.2
Barcol Hardness	21	22	18	27	25	23	18	20	21	20
Cast Tensile Strength (MPa)	70.3	50.7	54.6	- *	87.8	72.2	75.0	73.3	64.71	74
Cast Tensile Mod. (GPa)	3.78	3.65	3.89	- *	3.64	3.74	3.51	3.36	3.29	3.4
Cast Strain to Failure (%)	3.0	2.3	3.4	- *	4.50	4.04	4.00	4.50	4.87	4.5
Lam. Comp. Strength (MPa)	503	410	429	515	437	462	441	516	443	430
Laminate T.V.M. Strain (%)	2.2	-	2.0	1.9	2.15	-	2.00	2.50	1.98	-
Laminate ILSS (MPa)	52	52	50	45	49.0	53.3	54.0	46.0	47.15	57
ILSS Wet Retention (%)	79	81	90	92	87	84	82	98	87	-

*Ambient temperature cure alone is not recommended with this hardener.
** Data generated from 16 hours @ 55°C postcure.

Notes: For an explanation of test methods used see 'Formulated Products Technical Characteristics'. Please refer to the "Intro to Form Prods".pdf, which can be found in the Formulated product section on the website. www.gurit.com

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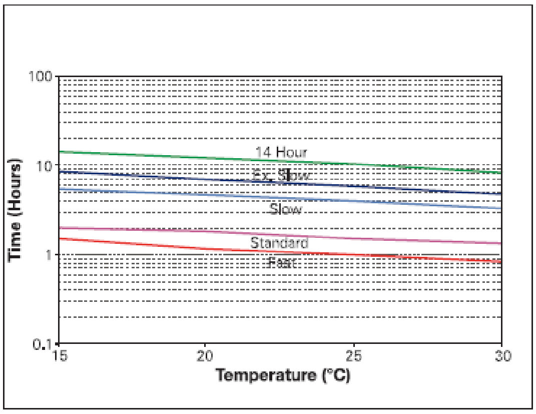
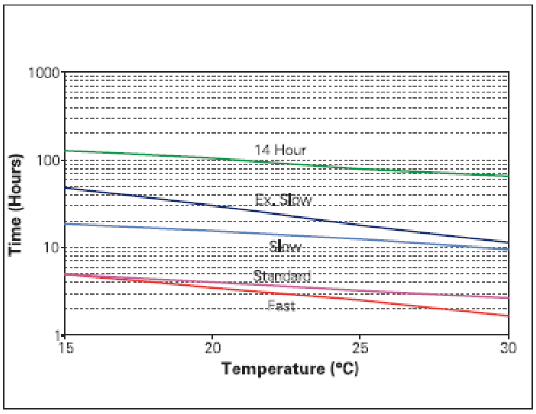
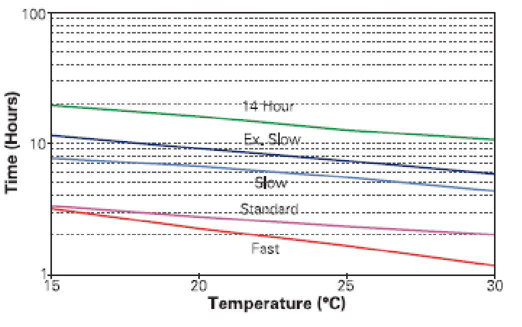
† All times are measured from when resin and hardener are first mixed together.



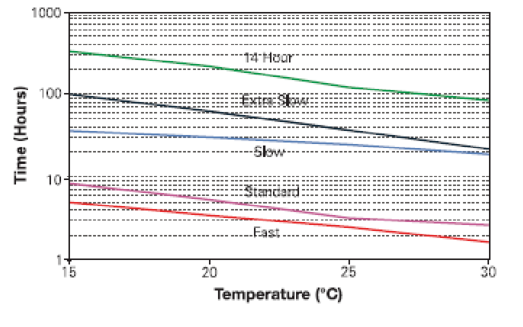


Properties (cont'd)

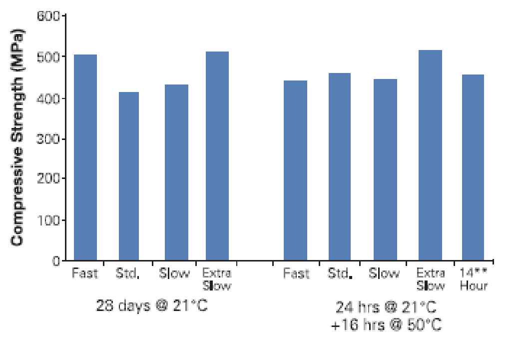
Latest Time to Apply Vacuum†



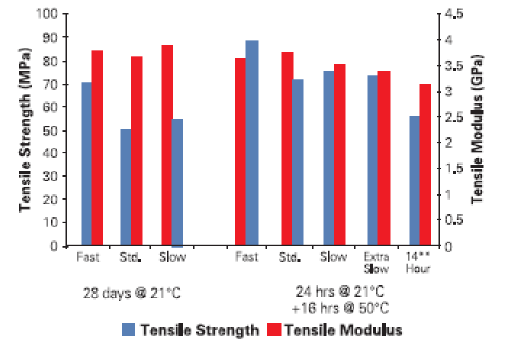
Theoretical Demould Time for Thin Laminates†



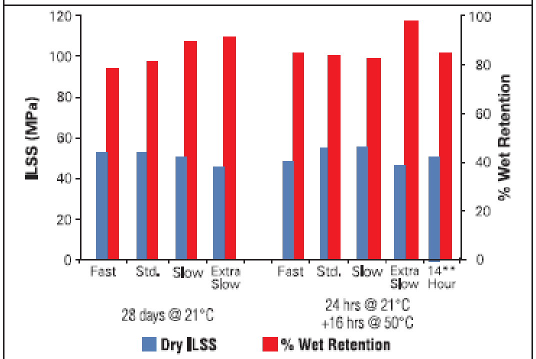
Compressive Strength of RE300 Glass Laminate



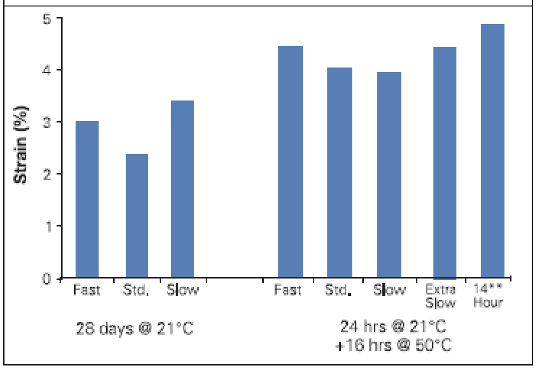
Tensile Properties of Castings



Interlaminar Shear Strength of RE300 Glass Laminate



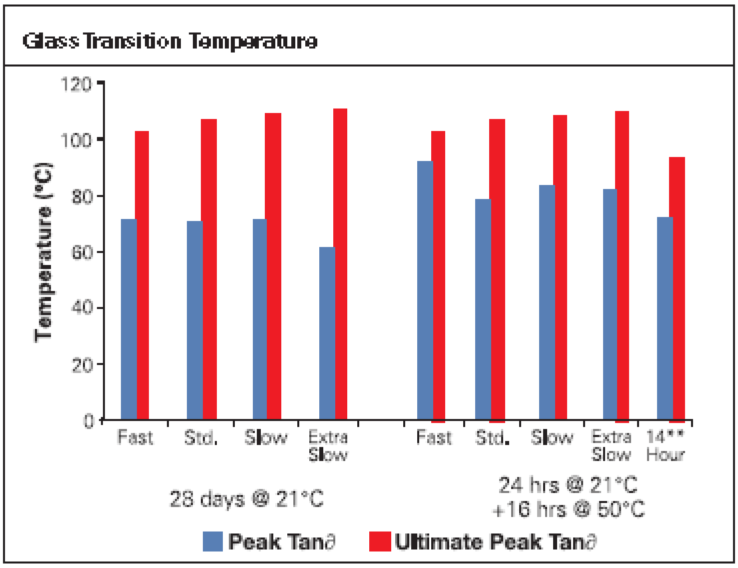
Strain to Failure of Castings



**Data generated from 16 hours @ 55°C Postcure

NOTES: For an explanation of test methods used see 'Formulated Products Technical Characteristics'.
All figures quoted are indicative of the properties of the product concerned. Some batch to batch variation may occur.
†All times are measured from when resin and hardener are first mixed together

Properties (cont'd)



**Data generated from 16 hours @ 55ºC Postcure

NOTES: For an explanation of test methods used see 'SP-High Modulus' Formulated Products Technical Characteristics'.

All figures quoted are indicative of the properties of the product concerned. Some batch to batch variation may occur.

†All times are measured from when resin and hardener are first mixed together

Fastening solution examples from Alcoa fastening systems catalogue