Preface:
This report presents the research and design of a Knowledge Transfer Programme between Sheffield Hallam University, Joseph Rhodes Ltd and myself to automate the process of producing off axis thermoplastic material at a rate suitable for the mass production market.

This study was conducted to investigate, design and manufacture a machine to automate the process of producing semi-finished off axis thermoplastic at a rate suitable for use in the mass production market. This study was brought about by the need in the industry to speed up the production of thermoplastic components for structural applications so it can be utilised in mass production bringing light weight vehicles to the market.

This project was allocated 30 months from June 2011 to December 2013 along with £100,000 of funding through the Knowledge Transfer Partnership Scheme, and £192,000 of funding through the SMART Grant to achieve the goal of producing a fully functional prototype machine to automatically produce off axis fibre reinforced thermoplastic material at commercially exploitable production rates.

Investigation of Production of Continuous off Axis Fibre Reinforced Thermoplastic Material.

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A thesis submitted in partial fulfilment of the requirements of Sheffield Hallam University for the degree of Master of Philosophy

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Collaborating Organisation: Joseph Rhodes Ltd

Abstract:

Fibre reinforced composites have been used in the engineering industry for many years since the discovery of glass fibre in 1930 and its first use to reinforce phenolic resin to form Bakelite. Since then thermoplastic and thermosetting composites have spread into almost every industry from marine to aerospace, automotive to motorsport, luggage to the hobby industry and even fashion. This vast range of applications for composite materials is due to their high strength to weight ratio, excellent impact absorption properties, lack of corrosion, and reformability. In recent years a government directive has forced automotive manufacturers to look at lighter and more efficient vehicles to reduce carbon emissions. This can be achieved by using fibre reinforced thermoplastics to replace steel panels throughout the vehicle.

Steel panels from a Nissan Qashqai were tested to determine the failure loads of each panel which the replacement thermoplastic material had to match or better. After extensive testing in a laboratory a tailored laminate lay-up with 5 laminate layers has been developed to replace structural steel components in vehicles. This tailored laminate stack up has a higher failure load than the steel components tested from the Nissan Qashqai while reducing the mass by at least 50%. The key drivers within the automotive industry are fuel savings and reduced vehicle mass, the use of this material and the potential it has in the mass production automotive industry can have a high impact on the overall mass of the vehicle which would invariably have a positive effect to the fuel consumption, thereby improving fuel economy in petrol and diesel vehicles, and increasing the range of electric vehicles.

Throughout this project a prototype machine was developed and built to achieve mass production of this 5 ply laminate at a rate of more than 345,000 laminates per year with a processing cost of 31p making it available to the mass production market. The estimated production cost represents approximately 2.4% of the finished product price.

Acknowledgements:

I would like to take the opportunity to extend my gratitude to the following people who helped throughout the course of the research and development project. I would like to thank Professor Graham Cockerham for his continued support, knowledge and guidance throughout the entirety of the project and Dr Syed Hassan for his knowledge on composites. I would like to thank the team within the company whose help and support ensured the continued justification of the project, this team includes Mr Ian Ridgway (Company Chairman), Mark Ridgway OBE (Managing Director), Barry Richardson (Marketing Director), Alaister Cooper (Finance Director), the manufacturing team, the drawing office, and Rhodes Technical services. I would like to thank material supplier Ticona, namely David Almond, for their support with material and connections. I would also like to thank Nissan Motoring UK, for their donation of vehicle panels both pre and post pressing for comparison purposes. I would like to thank the admin team (Patrick Egan and Sarah Durkin) at Sheffield Hallam University for their help and support. I would like to thank the Technology Strategy Board for their support funding the knowledge transfer partnership, along with the SMART Grant funding also provided by the Technology Strategy Board to help fund the machine build. I would like to thank Appleyardlees for their support and help filing a patent on the invention with this project. Last but not least I would also like to thank my family; Patrick McDonald, Catherine McDonald and Kirsty Leckenby for their continued help and support throughout the research and development project.

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Nomenclature

σ_A ....Total stress in the composite

σ_m ....Stress in the matrix

σ_f ....Stress in the fibre

f ....Fibre content by volume

σ1 ....Stress parallel to the fibre direction

σ2 ....Stress normal to the fibre direction

σx ....Stress in the x direction

σy ....Stress in the y direction

τ12 ....Shear stress normal and parallel to the fibre direction

τxy ....Shear stress in the x and y direction

C ....Cos

S ....Sin

Θ ....Fibre angle

Dm ....Mandrel diameter

Vt ....Tape velocity

Wt ....Tape width

VL .... Laminate velocity

WL ....Laminate width

Chapter 1 - Introduction

There is a growing need in the automotive industry to reduce carbon emissions in vehicles and make vehicles more efficient by increasing the miles per gallon. This can be achieved by improving the efficiency of the engine or reducing the mass of the vehicle making it lighter. One way of achieving a lighter vehicle is by using composite materials to produce the vehicle panels as opposed to steel panels currently used.

In this thesis the author has developed a prototype machine to automate the production of off axis continuous fibre reinforced thermoplastic material at commercially exploitable production rates. The following 9 chapters in this thesis show the author has;

- Deduced what the market needs are through a literature review in chapter 2.
- Tested steel samples from an automotive manufacturer in chapter 3.
- Evaluated methods of feasibly achieving mass production in chapter 4.
- Developed concept designs in chapter 5.
- Refined the concept design in chapter 6.
- Produced sample components in chapter 7.
- Evaluated methods of securing a finished component to a vehicle in chapter 8.
- Evaluated the finished machine in chapter 9.
- Evaluated the project and the conclusions in chapter 10.

Through this project the aims and objectives have been;

- To develop a light weight material to replace steel in mass production automotive applications with significant mass savings.
- Develop prototype machinery to produce replacement material at mass production rates.
- Maintain low material processing costs.

The prototype machine has been achieved by following the seven steps outlined in figure 1. These steps progressed the project from an initial idea, through a feasibility study, develop conceptual designs and result in a manufactured prototype machine.

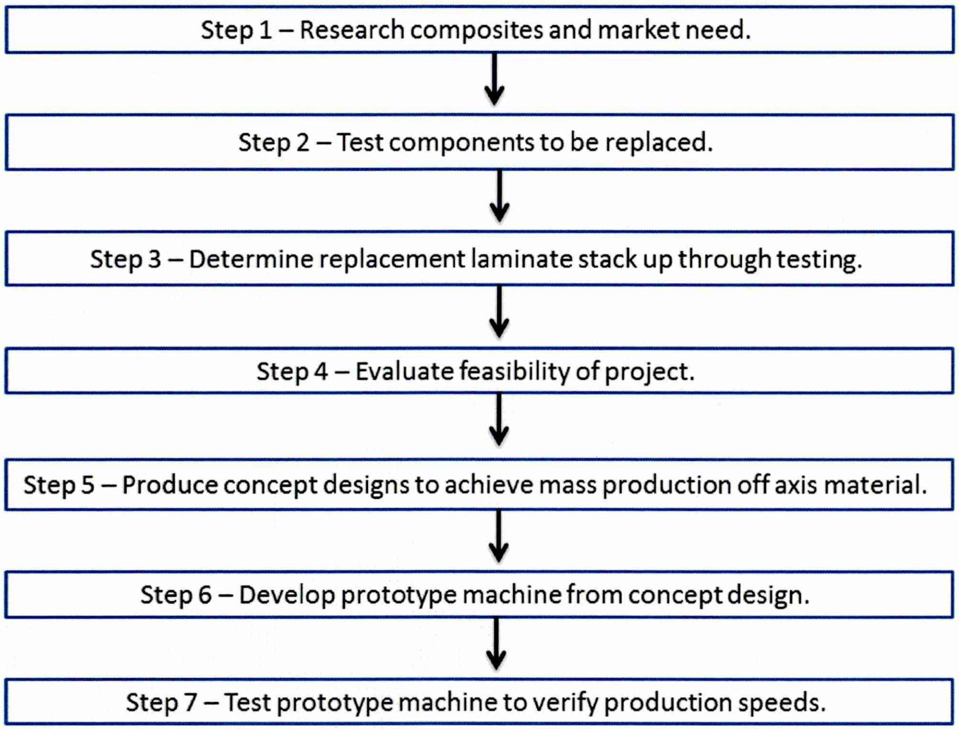


Figure 1: Programme Production Flow Diagram.

The initial concept design of the machine consists of the 4 stages shown in figure 2. These stages take the rolls of material supplied by the supplier, and process it into a multi layered off axis fibre reinforced thermoplastic laminate. Stage 1 produces a wide roll of unidirectional material from the rolls of material purchased from the supplier. Stage 2 then utilises the material widened in stage 1 and wraps it around a mandrel to form a continuous tube. This continuous tube is then compressed into a flat 2 ply sheet of material to form the off axis layers of material. Stage 3 also utilises the widened material produced on stage 1 and cuts the material into m^2 unidirectional sheets. Stage 4 then collates material from stage 2 and stage 3 which is then staked into a multi-layered off axis part consolidated laminate.

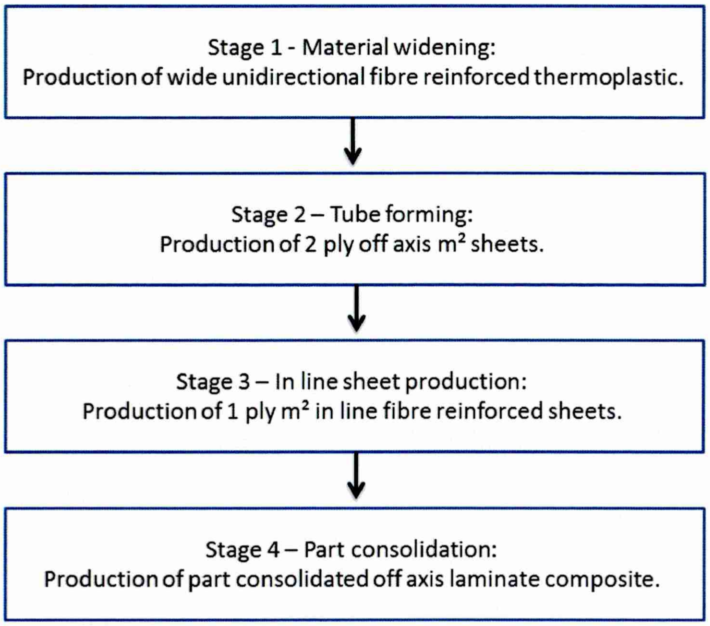


Figure 2: Concept Design Flow Diagram.

Throughout this project the author is responsible for testing steel samples provided by Nissan Motoring UK, and deriving the laminate stack up which was a suitable replacement for these steel components.

The author is also responsible for justifying the business case of the project through a feasibility study and performing trials to determine the most appropriate methods of forming a tube. In addition the author also conceptually designed the machine and proved each process of the concept machine individually to ensure the machine would have the desired outcome. Following the approval of the concept design by the board of directors at Joseph Rhodes Ltd the author briefed the design team in the specification of the machine and provided continued guidance and support to ensure the machine would have the correct function, delivering the required output speeds and product widths.

Further to this the author facilitated meetings with the research department at Warwick University to form finished components from the laminate stack up derived in the testing stage described in chapter 3 as well as securing a government grant of £192,000 to fund the machine build costs and filing a patent application to protect the design of the machine.

Chapter 2 – Literature review.

2.1 Literature Review - History of Fibre Reinforced Polymers:

Polymers have existed for tens of thousands of years in the form of natural polymers such as starch, cellulose and rubber. Although they have been used for millennia, polymers were only recognised in 1833 when Jons Jacob Berzelius discovered that two compounds could have the same composition but different molecular weights (Ginsberg 2003).

Polymers are a repeated chain of molecules linked with a covalent bond. Poly meaning multiple and mer being the repeated molecular chain. Figure 3 below shows polymerization of a monomer into a polymer, in this case ethylene into polyethylene.

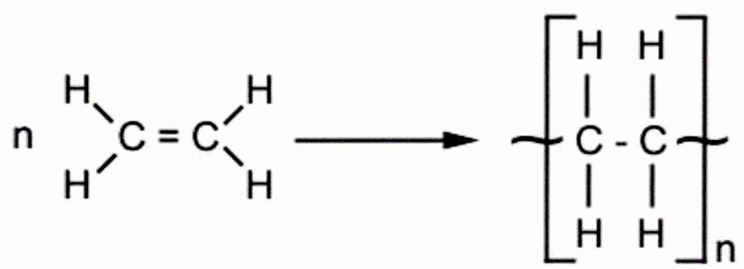


Figure 3: Polymerisation of Ethene (Science Aid 2009).

In the years that followed Berzelius's discovery many new materials were discovered such as vulcanised rubber by CH Goodyear in 1844 when he used sulphur to vulcanise natural rubber, the creation of the first artificial polymer by esterification of cellulose using a nitro sulphuric acid mixture in 1846 by C Schonbein, the discovery of polystyrene in 1866 by M. Berthelot and the creation of artificial silk by spinning a concentrated nitrocellulose solution. It was not until 1907 however that scientist Leo Baekeland introduced Bakelite which was the world's first synthetic thermosetting polymer which he discovered when trying to develop a binder for asbestos by combining formaldehyde with phenol to produce phenolic resin, a thermosetting resin polymer. The method used to produce Bakelite was later industrialised in 1910 which due to its excellent material properties such as being resistant to both heat and electricity as well as it being light weight, durable and easily moulded resulted in it being used for a vast array of applications such as radio casings, light switches, lamps, telephones, billiard balls and poker chips to name a few (Frontanille 2002) (Plastics Made it Possible 2014).

Many more polymers were discovered in the decades that followed the creation of Bakelite, most importantly polypropylene which was invented by Paul Hogan and Robert Banks of the Phillips Petroleum Company in 1951 when they produced a crystalline polypropylene when they fed propylene into a pipe packed with a nickel oxide catalyst with a small amount of chromium oxide. The experiment which required extreme pressures of 20-30 thousand PSI produced a crystalline polypropylene with the chromium producing a white solid material. This led to Phillips focusing their efforts on development of plastics rather than gasoline production, and within the year resulted in Hogan and Banks developing a new process to produce a high density polyethylene (HDPE), which only required a few hundred PSI of pressure. This discovery launched Phillips into a new industry manufacturing a family of plastics including polypropylene and polyethylene and within 6 years had taken it from the lab to commercial scale production. Polypropylene and polyethylene are both thermoplastics which means they can be melted and reformed an endless amount of times (American Chemical Society 1999).

There are two types of thermoplastic polymers: thermosets and thermoplastics:

Thermoset polymers cure through an irreversible process which cross links two polymers. Due to the cross linking of the polymers the plastic does not melt with the application of heat making thermosetting polymers ideal for applications where high temperatures are used, but long exposure to extreme temperatures can cause degradation and decomposition of the polymer.

Thermoplastic polymers on the other hand soften under the application of heat and harden through a change in physical state from liquid to solid as it cools. This means that the thermoplastic can be remoulded and reformed over and over again, and can even revert to its original form. Thermoplastics such as polypropylene boast a high strength to weight ratio, shrink resistance, excellent impact resistance, chemical resistance and are highly recyclable (Harper 1996)

The first truly synthetic plastic was Bakelite, which was invented by Leo Baekeland in New York in 1905. Leo Baekeland discovered that when he combined formaldehyde with phenol he produced the first phenolic resin which was hard, didn't soften under heat, and was water and solvent resistant (History Learning Site 2005) Baekeland used this as a binder for asbestos which at the time was moulded from rubber. Bakelite was the beginning of the age of plastics, and was used in radios, telephones and electrical insulators because it held its shape after being heated, and had great insulating and heat resistance properties (Victorian Source (no date)).

The use of modern fibre reinforced composites in the industrial world began in 1932 when a researcher at the Owens glass company accidentally directed compressed air at a stream of molten glass, producing fibres. This was combined with a polyester resin in 1936 to create a fibre reinforced thermoplastic (Marsh 2006).

Fibre reinforced polymer composites were used in the defence industry in the 1940's where they were utilised for their high strength to weight ratio as well as their resistance to corrosion by salt air and sea. By the mid 1940's in excess of £7,000,000 of fibre reinforced polymer material was being shipped, primarily for military use (American Composites Manufacturing Association (no date)).

In 1945 fibre reinforced polymers were used to make the first automobile with a fibreglass composite body when Owens Corning and William Stout developed the Stout Forty-Six. This experimental vehicle had very high build costs of $100,000 (Conceptcarz 2014).

Figure 4: 1946 Stout Scarab (Concept Carz 2014)

It was in the mid 40's that the benefits of fibre reinforced polymer composites were communicated to the public sector where they were utilised by the oil industry in 1948 for fibreglass pipes due to its corrosion resistance (American Composites Manufacturing Association (no date)).

The composites industry broke into the automotive sector in 1953 when Chevrolet used a fibreglass body for their first Corvette model. The use of the fibreglass body helped make this vehicle light and fast boasting excellent handling and 150 horse power. The production volumes of this vehicle were relatively low in comparison to present day production rates only 300 made in the first year with a price tag of $3,498 (Oldride 2014).

Then in 1956 the first high strength carbon fibres were discovered by Roger Bacon (Gorss 2003) when he was working on identifying the triple point of graphite (the temperature and pressure at which any given compound can be simultaneously a solid, liquid and a gas). Using equipment similar to that of a carbon arc streetlamp but working at much higher pressures, he noted that small amounts of carbon vapour would travel across the arc and deposit as liquid, however as Bacon reduced the pressure the carbon would go straight from the vapour phase to solid phase, forming a deposit on the lower electrode. Upon investigating the deposit he noticed that there were whisker like structures in the deposit which had a diameter roughly 10% that of a human hair, and were flexible as opposed to being brittle, these were filaments of perfect graphite. In the years that followed Curry Ford and Charles Mitchell heat treated Rayon (made from cellulose fibre) to 3000^{o}c, which at the time produced the strongest carbon fibres, until Bacon used a process called "hot-stretching" to stretch the graphite at temperatures of 2800^{o}c which orientates the layers of graphite to lie parallel to the axis making it stronger than the method used by Curry (Gorss 2003)

In the 1960`s both U.S. and British Navies were simultaneously producing minesweeper ships out of fibre reinforced composites due to them being better suited to the harsh marine environment than other materials; in addition fibre reinforced composites were non-magnetic in nature and had the ability to reduce the radar signature of the vessel. These attributes were also favoured by aircraft such as the F-117 Stealth Fighter and B-2 Bomber because a reduced radar signature increases their chances of flying undetected (American Composites Manufacturing Association (no date)).

It wasn't until the 1960`s that carbon fibre started to see practical commercial uses when two processes for manufacturing high strength and high Modulus carbon fibres were simultaneously invented using rayon and PAN (Polyacrylonitrile) precursor fibres. Rayon was used in a hot stretching process which involved stretching carbon yarn at temperatures in excess of 2800 ^{o}c which orientated the graphite layers to lie almost parallel with the fibre axis. The key to this process was to stretch the carbon yarn during heat up as opposed to only stretching the yarn when it had reached temperature, this resulted in a ten fold increase in Young's Modulus. Early carbon fibres were made from rayon, whereas now more than 90% of carbon fibres are made from PAN. Following this the successful commercial production of carbon fibre started with the aerospace and defence industries utilising this material which boasted high rigidity and strength while remaining lightweight (Oakridge National Laboratory 2009).

Carbon fibres from Bacon`s hot stretching which boasted a 172GPa Young's Modulus were subsequently used to reinforce phenolic resins in 1965 (Gorss 2003).

One of the first industries to use carbon fibre was is the aeronautical industry. Carbon fibres are used to reinforce phenolic resin in spacecraft heat shields, due to the ability of the resin to decompose slowly while absorbing the heat energy gained upon re-entry into the atmosphere (Gorss 2003).

Fibre reinforced polymers were also used in the Manhattan Project as the reinforced plastic hoops in the nuclear project in World War 2. This lead to the development of high performance composites in the 60`s and 70`s for rocket motor cases and tanks, which in turn also lead to the development of the Skylab laboratory orbiting Earth (shown below in figure 5). Almost 300 experiments took place including technical experiments, experiments on human adaptability to zero gravity, solar experiments as well as detailed earth resources experiments. The result of the astounding advancements of the Skylab proved that humans can work and live in space for extended lengths of time following its three sets of three-man crews which lived and worked there for a total of 171 days and 13 hours (American Composites Manufacturing Association (no date)) (Nasa 2014).

Figure 5: Skylab Orbiting Laboratory (Nasa 2014).

Carbon fibre has seen many uses since its discovery in 1956, including the use of scientific equipment in the 1970`s where it was used to measure extra cellular spike potentials across the membranes of neurones. Carbon fibre was used because the single strands had very small diameters of only 8 microns, and had a low electrode noise level (Bristol University 2013).

The sporting goods industry saw the use of carbon fibre for bicycle frames in 1975 which were constructed from carbon tubes connected with metal connections; however this type of frame saw frequent failure (Hudson 2013)

In the 1980`s, the civil engineering industry started to utilise construction grade carbon fibre to reinforce bridges that needed attention or re-working. This was a favoured material over steel bracing because it was much lighter, could be transported in a van as opposed to a heavy goods vehicle, and was much easier to apply to the bridge without the use of special equipment (Holloway 2013).

Glass fibre reinforced composites started to see mass production when in the 1980's the Pontiac Fiero was the world`s first mass production vehicle to utilise composite materials. These included three manufacturing methods for the composite materials which were sheet moulding compound, reinforced reaction injection moulding, and thermoplastic olefin which is a combination of polypropylene and rubber, only the first two of which are fibre reinforced. In 1984, the Pontiac made 136,840 Fieros, followed by a severe drop in subsequent years to only 26,243 in 1988. Although this was not the first application of composites into the automotive industry, it was the first high volume composite bodied car (American Composites Manufacturing Association (no date)).

Carbon fibre bicycle frames were introduced to the Tour de France by French manufacturer LOOK in 1986 when they released the KG86 under Bernard Hinault which had a better frame than the bicycle created in 1975 using carbon tubes with metal connections (Dansi 2013).

The most recent addition to the composites industry is a new material which is a self-reinforced thermoplastic composite which has both matrix and polymer made from the same material. This has the added advantage of excellent fibre-matrix cohesion, 100% recyclability, excellent shock absorption and noise reduction. The birth of this material came about in 1990 when researchers at the University of Leeds developed a process to produce a 100% thermoplastic 'self-reinforced'. This was produced by taking fibres of polypropylene and heating them up under pressure until the outer surface of the fibres melts, then cooling the tape to bind the structure as depicted in figure 6. This was then commercialised by BP under the registered trade mark Curv (Jones and Riley 2002).

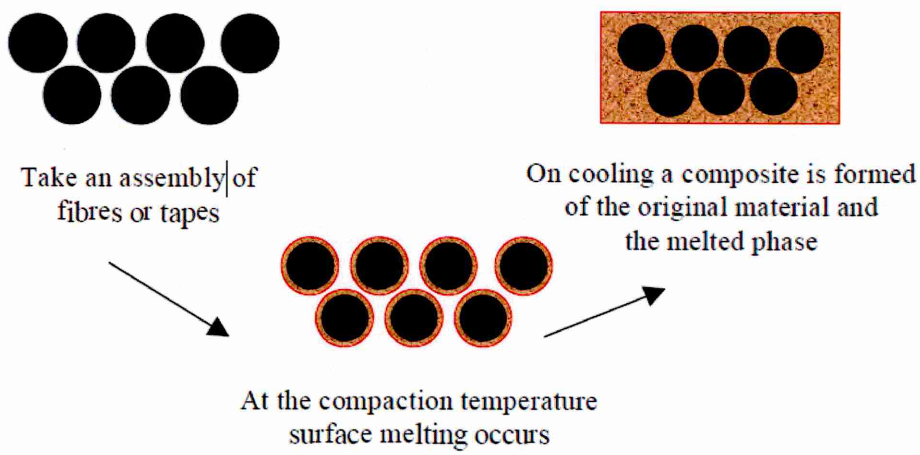


Figure 6: Hot Compaction Process (Jones and Riley 2002).

The SrPP has better mechanical properties than the isotropic polypropylene but as table 1 below shows apart from impact strength glass fibre reinforced unidirectional tape is still superior to Curv.

Table 1: Comparison of Polypropylene Based Materials (Jones and Riley 2002)

		Self-reinforced PP sheet	Isotropic PP	Random mat short glass/PP 40wt% fiber	Unidirectional glass/PP 60 wt% fiber
Density (Kg/m^2)		920	900	1185	1500
Tensile Modulus (GPa)		5	1.12	3.5-5.8	12
Tensile Strength (MPa)		180	27	99	350
Heat deflection temperature (°C)	455 kPa	160	100	157	
	1820 kPa	102	68	152	156
Notched Izod impact strength (J/m)	+ 20°C	4750	200	672	1600
	– 40°C	7500	brittle	brittle	
Thermal expansion (/°C x 10^{-6})		41	96	27	21

Until 1991 the US Department of Defence and the defence industry drove the carbon fibre industry at which point the end of the Cold War and collapse of the USSR resulted in consolidation and restructuring of the defence industries through various acquisitions which caused a sharp drop in the demand for carbon fibre. This drop in demand saw the carbon fibre industry reduce operations to less than 60% capacity between 1995 and 2000, reduce the price of carbon fibre, and cause carbon fibre to expand into automotive applications, aerospace, sporting goods, energy and industrial applications. All of this had a positive effect on carbon fibre consumption by 2002, resulting in increased demand and the need for carbon fibre to be produced at affordable prices in turn causing an expansion in carbon producers' manufacturing capacity to meet competition in the market (Oakridge National Laboratory 2009).

The UK government have set a directive urging the automotive industry to reduce carbon emissions to 90g/CO_2 by 2020 (Rofique et al 2011). Automotive manufacturers are looking at achieving this in 2 different ways: reducing vehicle mass and improving vehicle performance which has brought about an ever increasing demand for lighter materials to be used in the automotive industry.

In response to this directive Audi are producing the spare wheel well for their A8 using highly reinforced polyamide called durethan dp bkv 60 h2.0 ef, this was chosen over steel due to its high draw ratios, light weight and ability to be formed into complex geometry. The spare wheel well is comprised of 60% glass fibres and has 70Kg of weight attached, such as the spare wheel, battery, vehicle jack and tools with the spare wheel well component having a mass of 9kg. Due to the complex geometry and deep draw of the finished spare wheel well it does not lend itself to stamping operations, which is why the injection moulding process is the preferred option (Reinforced Plastics 2010).

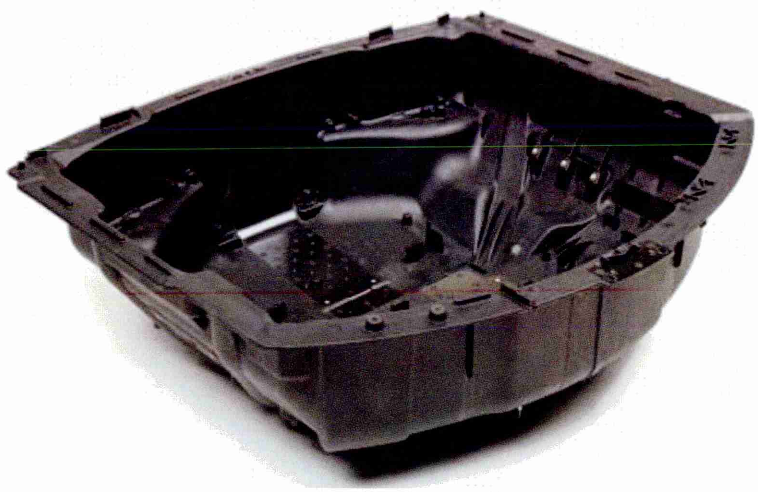


Figure 7: Audi A8 Spare Wheel Well (Reinforced Plastics 2010).

According to Renault, at the beginning of 2013 they produced some vehicle components for the new Clio out of fibre reinforced polypropylene. Their method of manufacture is to place a continuous glass fibre 3D woven structure of the component into a mould, then inject the mould with polypropylene and short glass fibres so the structure has both a continuous glass reinforced structure, and short glass fibres. The expected production volumes for the new Clio are in the region of 400,000 across the whole Clio range. In addition, other composite components currently used by Renault include a polyester resin reinforced with glass fibre which is utilised in the form of a sheet moulding compound in their Megane Coupe, a model which will run until 2016 (Piccirelli 2012).

In modern low volume production automotive and motor sports applications carbon fibre is the preferred composite when it comes to replacing steel structures. This is due to its high strength to weight ratio, aesthetic appearance and its ability to be used in applications which involve high temperatures and corrosion resistance. Carbon fibre is a good replacement for steel as the mechanical properties can be matched or improved while reducing the mass of the component drastically; however there are several factors which work against carbon fibre, those being: production cycle time, cost and recyclability. The cycle time is due to the carbon using an epoxy resin which has a long curing time, and requires both temperature and pressure to reduce the cycle time from the curing time of being left to "air cure". Because of this, carbon fibre is not used in high volume applications, rather it is used in specialised high end expensive automotive vehicles, large aircraft, and aeronautical applications which are all low volume production.

The cost of Carbon Fibre is also a key reason for it not progressing with the momentum that it could, due to it costing in excess of 32 times the price of steel per ton (World Steel Prices 2013). The price of steel was $721 (£461) per ton in December 2012, compared to the cost of carbon fibre which for dry fibre, depending on the tow (amount of intertwined filaments), varies from £36,000 per ton for 3k tow to £14,000 per ton for 48k tow (Easy Composites 2013). The prices of carbon fibre fluctuate depending on whether it is a dry fibre, a woven fabric, or a prepreg. 3k tow is a twine of 3,000 strands of carbon fibre, while 48k tow is a twine of 48,000 strands of carbon fibre. The volume is consistent and so is the diameter of each carbon fibre strand so the length of the continuous fibre decreases with the increasing tow value (Craig 2013).

Figure 8: 12k Tow carbon fibre (Easy Composites 2013).

By way of comparison as the price of a carbon fibre prepreg (fibres and uncured resin) ready for the mould is considerably higher at £110,256 for prepreg fabric from easy composites (Easy Composites 2013). The price from an industrial supplier would be lower than this but the industrial suppliers contacted would not supply pricing information. Due to the disadvantages of price and curing time for carbon fibre thermosets, they are mainly restricted to industries which have a lot of money and time to invest and use high end components such as those found in motor sport, aerospace and aeronautical applications.

One of the principal uses for carbon fibre is in aerospace with customers such as Bombardier, Boeing, and Airbus using carbon fibre to produce aircraft such as the Boeing 787 DreamLiner which is 50% composite as shown in figure 9, and the Airbus A350 as shown in figure 9 which is 52% composite which reduces the mass of the aircraft greatly (Boeing 2013) (Aviation News 2013).

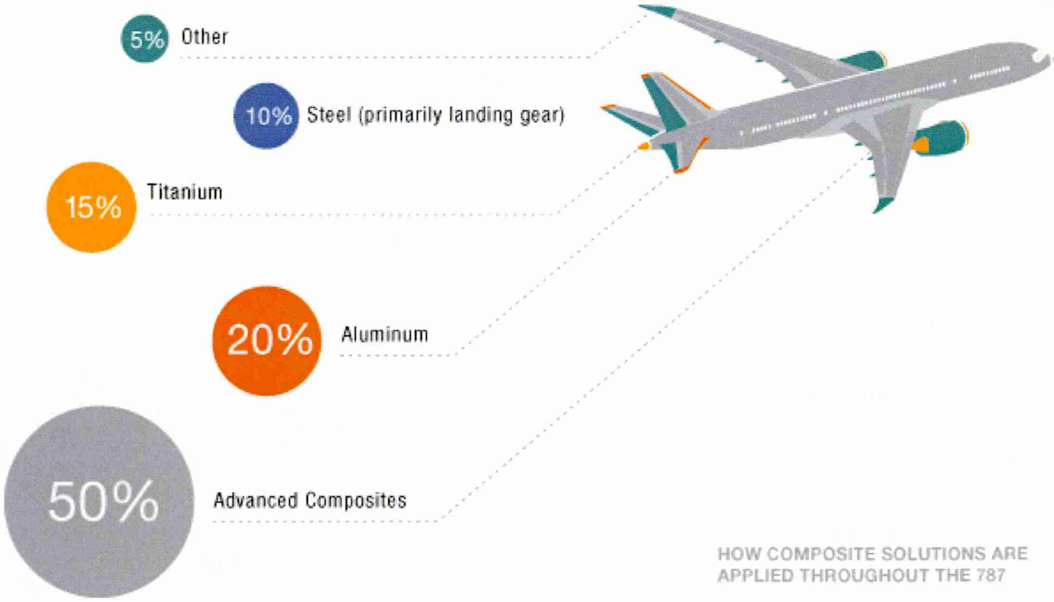


Figure 9: How Composite Solutions Are Applied Throughout The 787 (Boeing 2013).

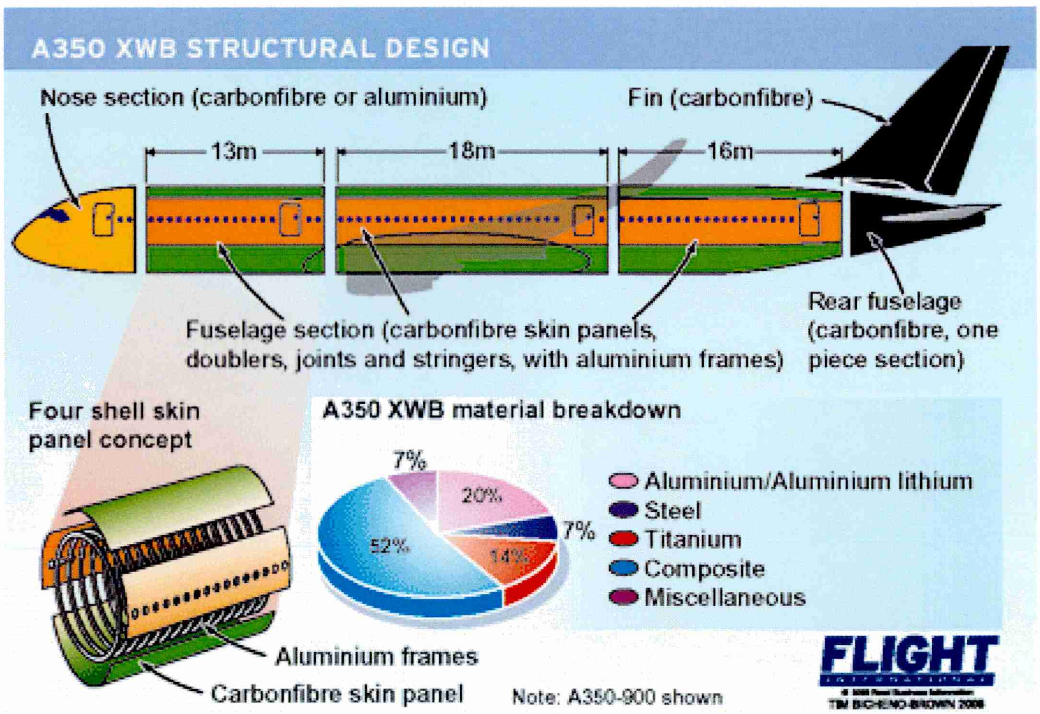


Figure 10: Airbus A350 Composite Representation (Aviation News 2013).

The most recent use of Carbon Fibre in the automotive sector is by BMW producing a complete monocoque chassis for the i3 and i8 models using a 3D weave of carbon fibre and a fast cure epoxy resin. This resin produced by Momentive Specialty Chemicals Ltd with a 5 minute cure time is being utilised to achieve the quick cure of the monocoque chassis. Although this is a major breakthrough in the use of carbon fibre in the automotive industry, the production volumes are still relatively low at less than 40,000 for the i3 and less than 15,000 for the i8. BMW formed an alliance with SGL Group, a carbon fibre manufacturer based in Munich to satisfy their annual appetite of 3,000 metric tonnes of carbon fibre for not only the i3 and i8 but some of the M series range of vehicles they also produce. This collaboration between an automotive manufacturer and a carbon fibre manufacture has set off a trend as more follow suit, for example General Motors have joined forces with Teijin, a Japanese carbon fibre manufacturer in their efforts to achieve a true 60 second manufacturing process using carbon fibre prepreg with a thermoplastic matrix such as polypropylene or polyamide which does not require long curing times to allow cross linking of the resin and can also be reformed (Sloan 2012).

2.2 Manufacturing Methods of Fibre Reinforced Composites:

There are several differences between thermosetting composites and thermoplastic composites, the most defining of which is that once thermosetting composites have been formed they remain in a solid state due to the cured resin polymer, whereas thermoplastics can be re-formed and melted under the application of heat. The solid state of thermosetting polymers is caused by the polymers cross linking during the curing process to create an irreversible chemical bond; this gives thermosets a hard chemical and heat resistant characteristic as well as structural integrity. Due to these properties thermosets are ideal for high heat applications, enclosed components and electronics. In some applications the benefits of thermosets are heavily offset by the downsides which are their inability to be recycled, and the fact they cannot be remoulded or reshaped.

Thermoplastics on the other hand are highly recyclable, can withstand high impact, are chemical resistant and can be reformed. Thermoplastics change physical state during curing, from a softened plastic form to a solid form, as opposed to a chemical reaction which occurs during the thermosetting curing process. Due to the material properties of thermoplastics they are ideal for high stress mechanical applications. The disadvantage of using a thermoplastic as opposed to a thermoset is that it may soften or melt if used in high temperature applications, as well as generally being more expensive than thermosetting polymers (Harper 1996).

There are currently 6 manufacturing processes for producing fibre reinforced polymers:

Spray gun,

Sheet moulding compound,

Reinforced reaction injection moulding,

Hand lay-up,

autoclaving

and pultrusion

2.2.1 Spray Gun Method

The spray gun method uses a gun to spray the polymer and chopped short length fibres into an open mould, so the thickness can be built up over time by passing the gun over it an appropriate number of times. This method is very messy, slow, and the quality and strength of the finished component are dependent on the skill and experience of the operator. This method can take hours to produce a single component depending on the size and complexity of the finished component. Due to the nature of the chop gun method repeatability is an issue, as well as health and safety also being an issue with the risk of the operator inhaling vapour from the resin and indeed the resin itself as it is being sprayed. Applications for the spray gun manufacturing method include making small to medium volume components, boat hulls, bath tubs, storage tanks and air handling equipment. This method would be used with a resin which requires curing, as opposed to a thermoplastic which would need to be in its molten state, making it unsafe for the operator and allowing the possibility for the plastic to solidify prior to contact with the mould.

Figure 11: FRP Chop System (Graco 2013).

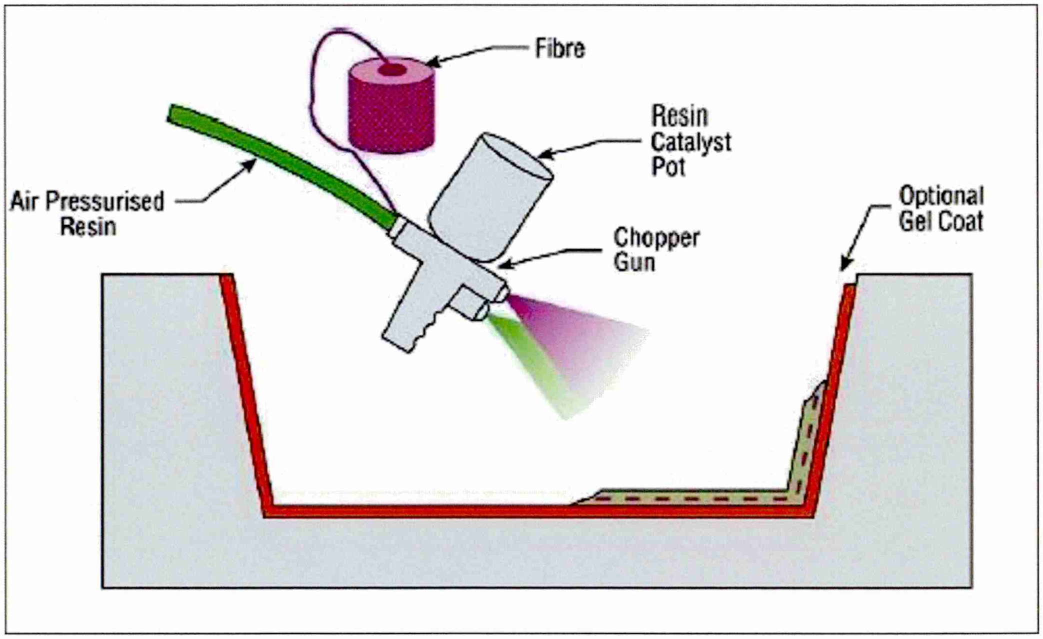


Figure 12: Spray Gun Manufacturing Method (Autospeed 2013).

2.2.2 Sheet Moulding Compound

Sheet moulding compound is a composite board made from a thermoset polymer and fibre reinforcement and is produced by dispersing reinforcement strands into a bath of polymer resin. The reinforcement strands increase the strength properties of the polymer, however the exact strength characteristics of the material are mainly dependant on the volume of reinforcement fibres dispersed and their orientation. This method of manufacture is used to produce components such as bath tubs (as well as the spray gun method), seats for cinemas and stadiums as well as electronic machine housings. These sheets are left to stand for a few days after manufacture to allow the correct viscosity to be reached prior to pressing of the finished component. The disadvantages of sheet moulding compound are the curing times of the sheets as they are being made as well as the component not having a specific strength or defined characteristics. Figure 13 below shows how sheet moulding compound is made.

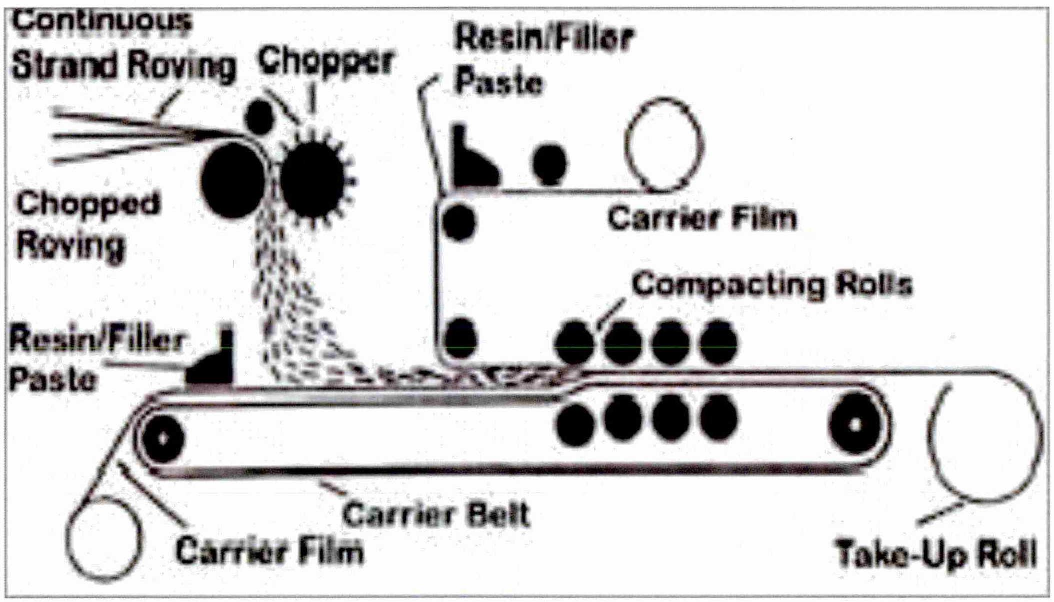


Figure 13: Sheet Moulding Compound Manufacturing Process (Frp Raw Materials 2013).

2.2.3 Reinforced Reaction Injection Moulding

This uses two resins which are heated up independently and mixed with glass fibres in a mixing container. Once the mixture has been blended it is injected into a mould cavity and compressed into the profile of the end component. Other forms of this manufacturing method include the use of a glass fabric matt which is stronger than normal reinforced reaction injection moulding and can be used in structural applications. The disadvantages of reinforced reaction injection moulding are that the reinforcing fibres are scattered and disordered throughout the product, so a specific strength and defined repeatability can become an issue. This method would be used to produce injection moulded components such as car spare wheel wells, bumpers, and front and rear wings. The two resins and reinforcement are mixed prior to moulding as shown in figure 14. This manufacturing process can only be used with thermosetting polymers as a reaction between the resins causes them to cross link and cure upon the application of heat and pressure in the mould.

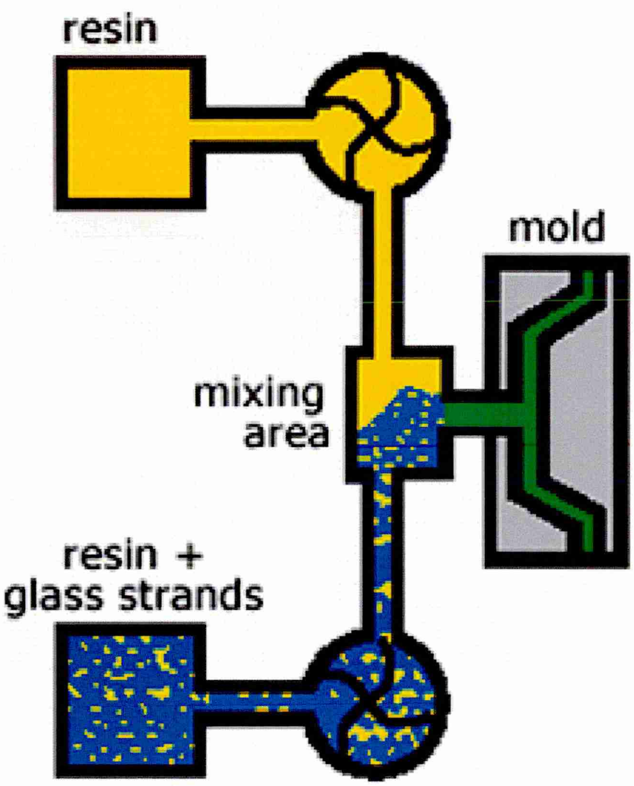


Figure 14: Reinforced Reaction Infection Moulding Manufacturing Process (Composites Owens Corning 2013).

2.2.4 Hand lay-up

Hand lay-up is a process which uses fibre reinforcement sheets and resin. These layers of reinforcement are placed either onto or into a mould depending on whether the mould is male or female. Resin is then painted by hand into the layer of reinforcement before another layer of reinforcement is added. This process is completed a number of times until the desired thickness has been achieved, and the required strength characteristics have been achieved. The disadvantages of this process are that it is a very messy and labour intensive process, there are repeatability issues as the quality of the finished product is dependent on the operator`s experience and skills, as well as there being inherent health issues with prolonged exposure to the resin. This manufacturing process is primarily used to make thermosetting components for motorsport applications, motorbike components and other low volume components.

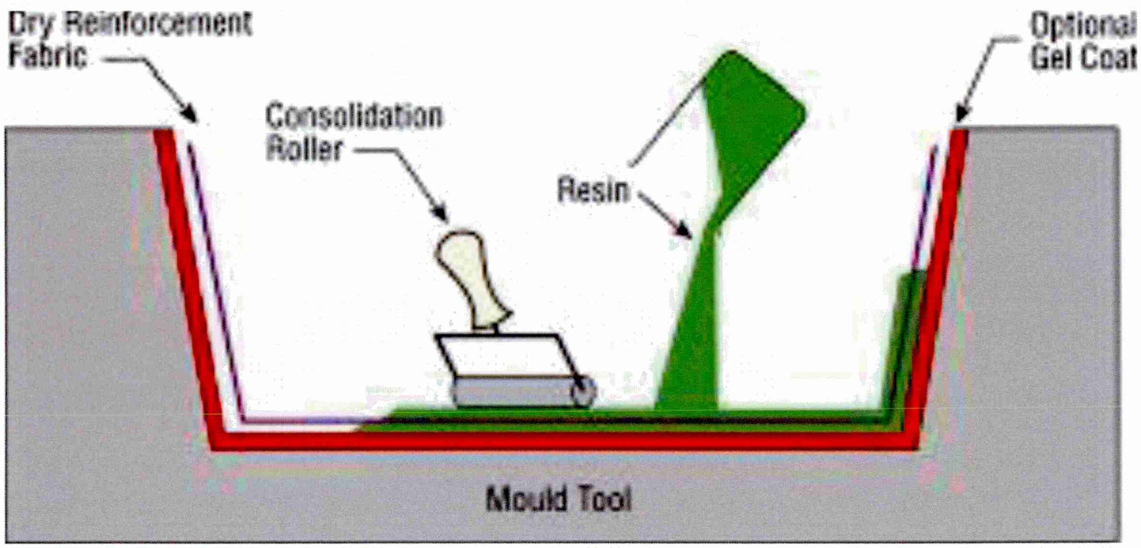


Figure 15: Hand Lay-up (Net Composites 2013).

Figure 16: Hand Lay-up Production (BFG International 2013).

2.2.5 Autoclave

Autoclave forming is a process used for thermoset composite component manufacture such as carbon fibre aeroplane wings etc. This manufacturing process applies heat and pressure inside a pressure vessel to allow the composite component to cure. With the pressing being conducted inside a pressure vessel the pressure exerted upon the component and mould is even. This is used to cure thermosetting composites which can be as large as an aeroplane wing, and requires constant heat with uniform pressure. Figure 17 shows a composite component in a mould entering an autoclave ready to begin the curing process.

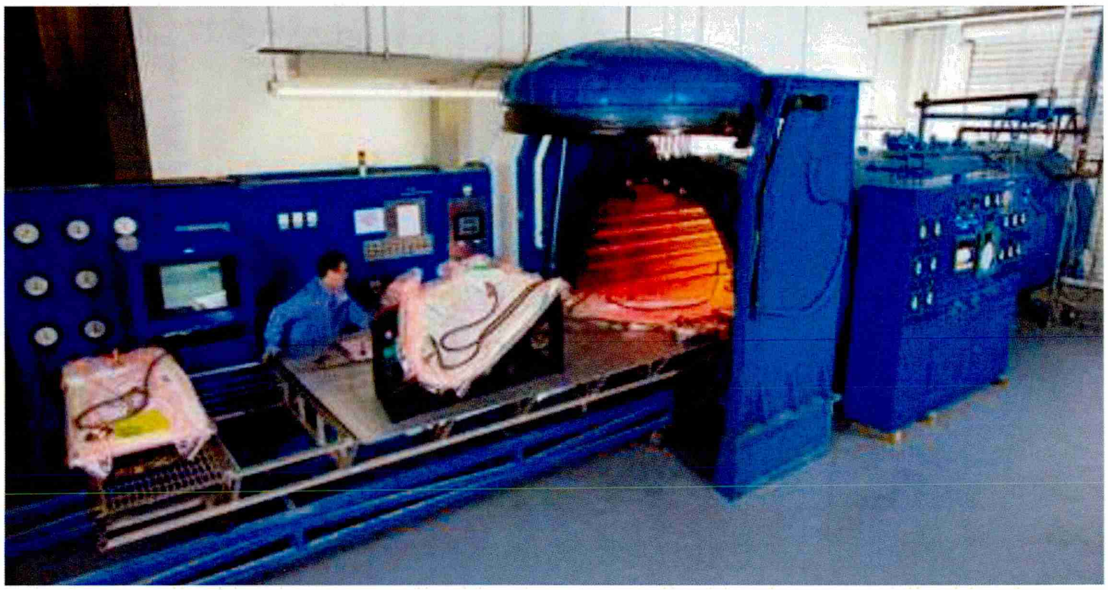


Figure 17: Autoclave Manufacturing Process (Composites World 2013).

2.2.6 Pultrusion

The pultrusion method of production takes a fibre reinforcement, submerges it in a bath of polymer, pulls it through a die and either dries it through a series of tensioning rollers before coiling it up or pulls it into a component shape. When it is coiled up it is known as a unidirectional tape due to all of the reinforcement fibres being in one direction. This material produced can then be used to create a laminate stack up, with the stack up consisting of plies in various orientations done by hand.

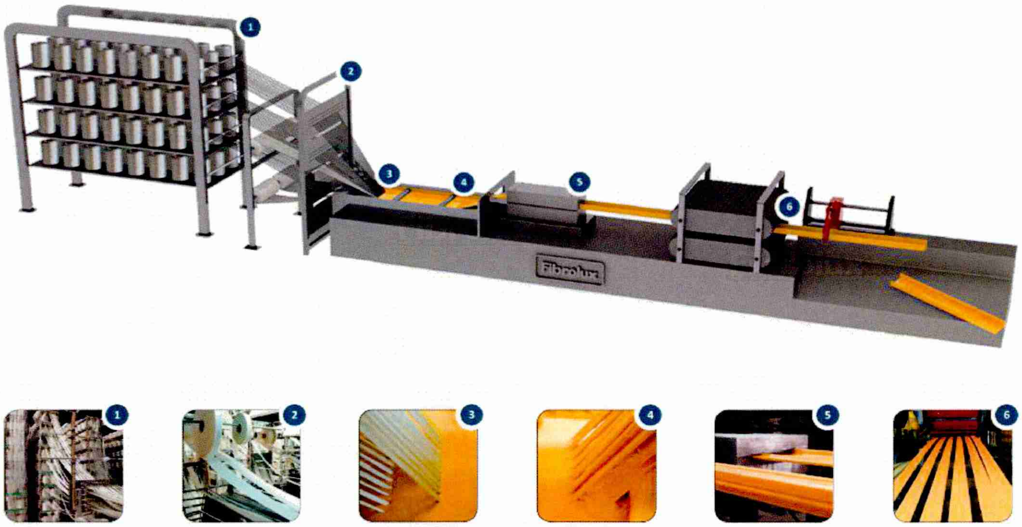


Figure 18: Pultrusion Manufacturing Process (Fibrolux 2013).

2.3 End of Life Uses For Fibre Reinforced Composites:

Composites can be recycled by 3 main methods. These methods are mechanical, thermal and chemical processing.

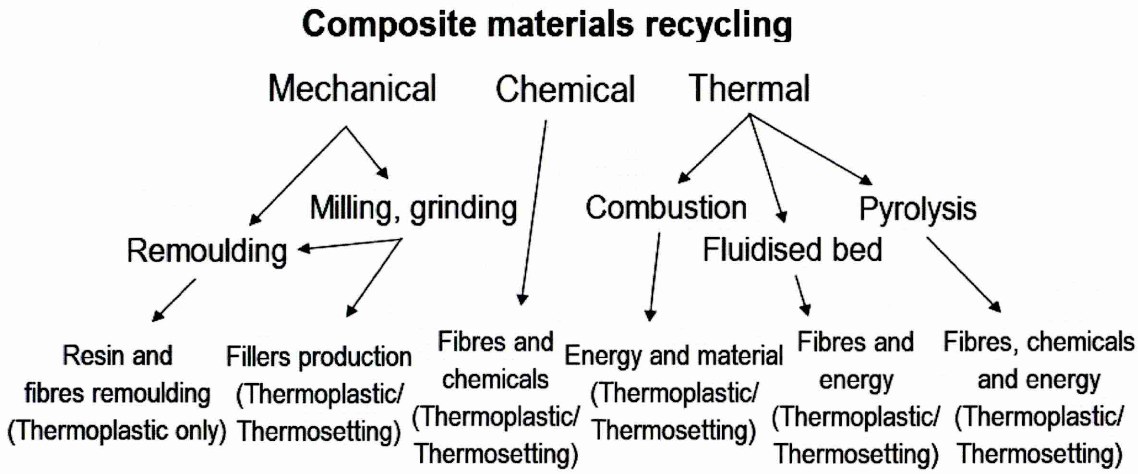


Figure 19: Recycling Processes For Thermoplastic And Thermosetting Composites (Otheguy et al 2009).

2.3.1 Mechanical Recycling Methods;

Thermosets and thermoplastics can be milled, ground, and shredded to reduce their size once the component has reached the end of its life, but only thermoplastics can be remoulded by changing the physical state. The matrix is used as a filler when remoulding new components. Thermosets on the other hand cannot be remoulded following shredding, milling or grinding due to the matrix being cross linked and the process being irreversible. Using the recycled thermoplastic as a filler is not a viable option due to the filler material being more expensive than virgin materials such as silica (Pickering 2006).

2.3.2 Thermal Recycling Methods:

Both thermoplastic and thermosetting plastics can be recycled using thermal processing methods. These include combusting the composite to release its calorific value to be used for energy purposes.

The composite can be processed on a fluidised bed where hot air at 400-700^{o}c is blown through a silica sand bed with the fibres being filtered from the hot air stream emerging from the bed, while the gas containing the matrix is recovered in an afterburner to release the energy. The resulting fibre reinforcement from these three methods is short fibres and experiences strength losses of up to 25% (Allred 2000).

The composite can also be processed through pyrolysis which involves heating the composite up to extreme temperatures turning the resin into a gas and oil, leaving behind a char of fibre reinforcement (Wood 2010).

2.3.3 Chemical Recycling Methods:

The composite components can also be recycled using chemical processing to leave the fibres and chemicals. This is done by using chemicals or super critical fluids to chemically decompose the matrix which can then be used for energy.

This method however has health issues with the use of harsh chemicals, and the resulting chemicals from the matrix and decomposition chemical can require further processing to release the energy (Poulakis and Papapyrides 1997).

2.3.4 Reforming a Component From Pyrolysis

The fibres left over as a result of the pyrolysis process resemble a fluffy cotton ball (shown in figure 20 below), which is then shaped into a preform of the final component (shown in figure 21) before being pressed and mixed with resin to create the end component (shown in figure 22).

Figure 20: Reclaimed Carbon Fibre From An F-18 (Wood 2010).

Figure 21: Preform Made From F-18 Recyclate (Wood 2010).

Figure 22: Finished Component; Chevrolet Corvette Wheelhouse (Wood 2010).

2.3.5 Future Potential End Of Life Uses For Fibre Reinforced Composites.

Research into further uses for recycled carbon fibre also includes using the short individual filaments in a fluffy form which can be used as a heating fabric in pizza bags and gloves (University of Nottingham 2013).

Although research will continue into recycling carbon fibre until a recycled woven mat form has been achieved, or the recyclate has aligned fibres enabling the determination of the recycled products fibre orientation, as opposed to short randomly orientated carbon fibres from injection moulded pellets. These forms would be desired over the short fibre pellets as the composite market understands mats not pellets, with the woven carbon fibre mats having fibres in both the 0 and 90 degree orientations, which enables the prediction of true component strength which is much more reliable (Wood 2010).

2.3.6 Conclusion:

The objectives of the project have been justified through the literature review, to demonstrate that the mass production of an off axis fibre reinforced composite would potentially have a market in the automotive industry. As an important part of the project I had to source materials from suppliers for testing. There were two materials found which had properties that would be useful for engineering applications, Celstran produced by Ticona, and Plytron produced by Elekon.

Key factors to consider when choosing the material were price, widths of material available, mass of the material, and fibre volume. These two materials were chosen due to their high fibre volume (60% and 70%), they were low cost and they were available in large widths (300mm wide for Elekon and 343mm (13.5") wide for Celstran). They will both be tested to determine which is best for mass production automotive applications.

2.4 Strength Prediction of Continuous Fibre Reinforced Composites:

2.4.1 Achieving Off Axis Fibre Reinforced Thermoplastic

The fundamental principle of producing continuous off axis thermoplastic is based on the method used to produce cardboard cores in the paper industry for applications such as wrapping paper cores, Pringles tubes, toilet roll cores etc. The automation of off axis thermoplastic unidirectional tape is achieved by wrapping the unidirectional thermoplastic tape around a mandrel at a pre-determined angle (chosen from testing samples), then joining the leading edge of one wrap to the receding edge of the previous wrap to form a helical weld. The tube which is formed using this process is then compressed and collected on a roller. Figures 23, 24, 25 and 26 show the unidirectional thermoplastic material being wrapped around the top of the mandrel and wrapping around to form a continuous tube. The blue lines shown in figures 23, 24, 25 and 26 are for illustration only to represent the direction the fibres are orientated in within the composite.

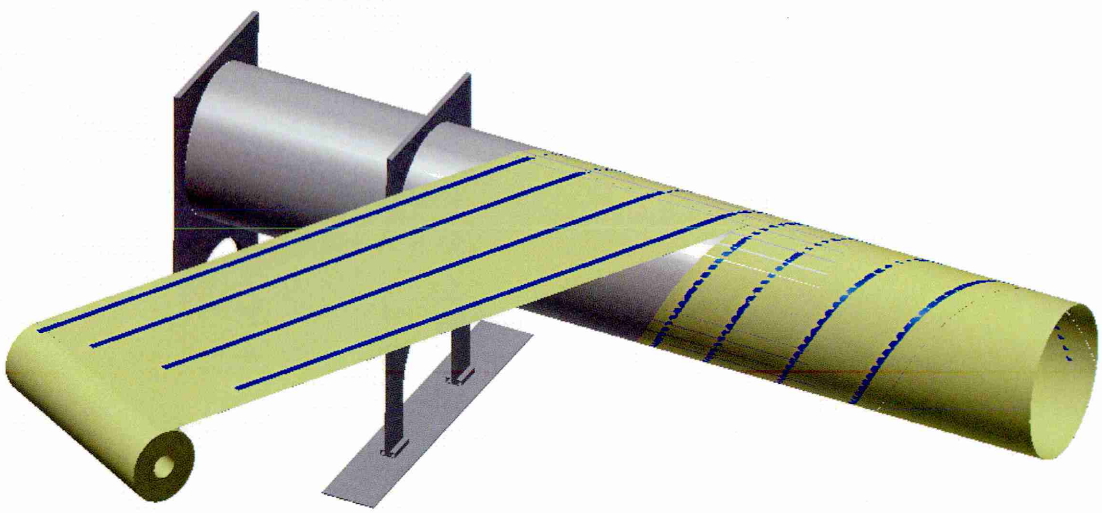


Figure 23: Conceptual Design of Off Axis Processing of Unidirectional Tape

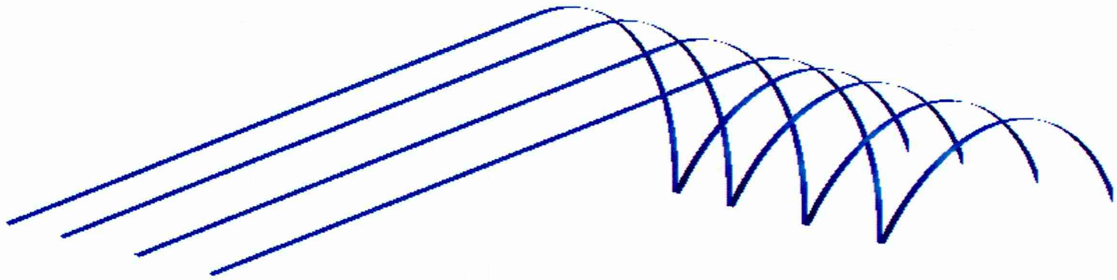


Figure 24.Off Axis of Unidirectional Tape With Fibre Trace

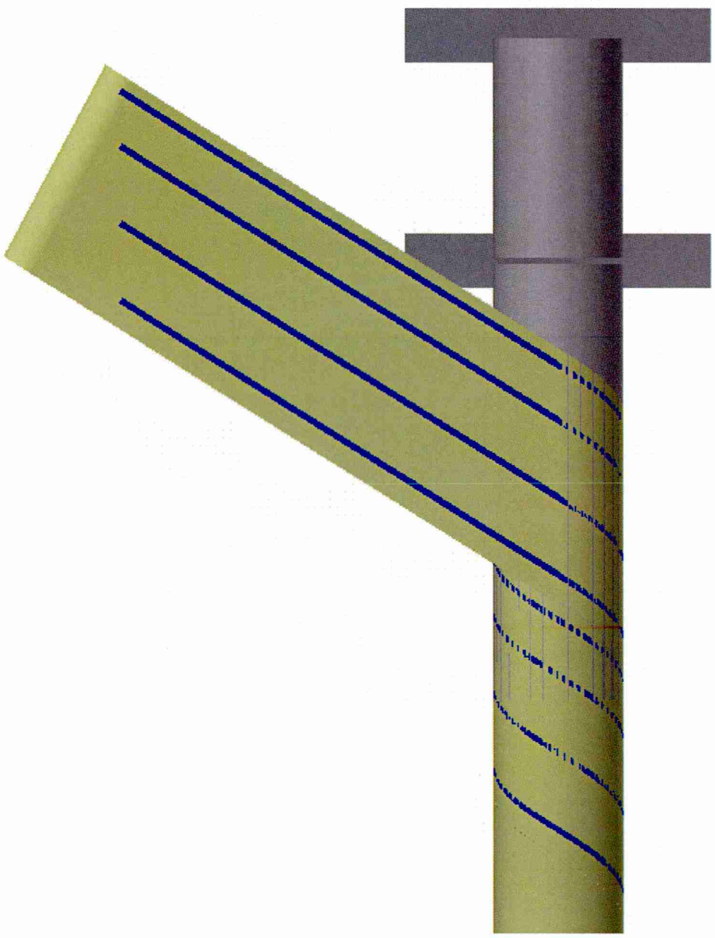


Figure 25.Top Down View of Off Axis Processing Method.

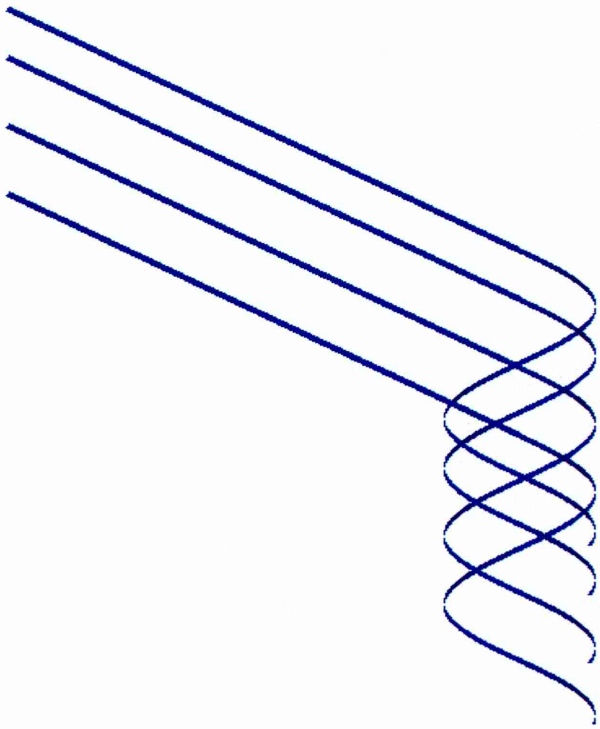


Figure 26: Fibre Orientation Trace

There are several possible replacement materials to investigate for the replacement of structural steel components, these materials include Curv (a self-reinforced polymer where both matrix and fibres are polypropylene), Armordon (another self-reinforced polypropylene), Plytron (a 60% glass by weight fibre reinforced polypropylene) and Celstran (another 70% glass by weight glass fibre reinforced polypropylene). The self-reinforced polypropylene is of interest to this project due to it being easily recyclable with the fibres and matrix all being the same material, and the inherent shock absorption capabilities of polypropylene.

The two self-reinforced polypropylene materials (armodon and curv) were woven mats made of self-reinforced polypropylene (SRPP) ribbon which was 3mm in width. Because they were made using a woven mat, they did not lend themselves to the above mentioned production process and were not taken further in the investigation however the possibility of making the replacement components out of srpp in the future may be made possible with the production of unidirectional srpp tape in greatly increased widths.

Plytron and Celstran were taken through to testing as they were available in workable widths and could be wrapped around a mandrel to produce a tube. The data sheets for Plytron and Celstran can be found in appendix 1 and 2 respectively.

2.4.2 Theoretical Prediction:

To determine the appropriate laminate to replace structural steel in automotive applications, I must determine the theoretical strength of each layer at varying angles taking into account that in tensile testing the components failure modes will be tensile and shear due to the laminate layers being laid up at various angles. To do this I shall use the Halpin-Tsai equation to determine the average ultimate tensile strength of the composite taking into account the matrix and fibre volume fraction.

Using the equation:

$$\sigma_A = \sigma_m f + (1-f)\,\sigma_f$$

Equation 1: Halpin-Tsai rule of averages equation

Where σ_m and σ_f and σ_A represent the ultimate tensile strength of the matrix, fibre and average respectively and f is the volume fraction. Using the ultimate tensile strength of polypropylene of 40MPa (Mascia 1982) and glass fibre being 2000MPa (Mascia 1982), a fibre volume of 35% (60% fibre by weight) taking the raw material Plytron as example from Elekon and equation 1 above would result in a tensile strength of;

(0.65 x 40) + ((1-0.65) x 2000) = 726MPa

Therefore, Plytron has an ultimate tensile strength of 726MPa in a direction parallel to the fibre direction.

Using Celstran by Ticona with a fibre volume of 44% (70% fibre by weight) and equation 1 above would result in a tensile strength of:

(0.56 x 40) + ((1-0.56) x 2000) = 902.4MPa

Therefore, Celstran has an ultimate tensile strength of 902.4MPa in a direction parallel to the fibre direction.

As Celstran is the stronger of the two materials the author shall concentrate on producing the optimum laminate with this material as it will result in a thinner laminate, therefore a lighter component.

To calculate the laminate UTS at an angle to the fibre direction the following relationship can be used;

$$\begin{vmatrix} \sigma 1 \\ \sigma 2 \\ \tau 12 \end{vmatrix} = \begin{vmatrix} C^2 & S^2 & 2CS \\ S^2 & C^2 & -CS2 \\ -CS & CS & C^2\text{-}S^2 \end{vmatrix} \begin{vmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{vmatrix}$$

Equation 2. Halpin-Tsai Matrix

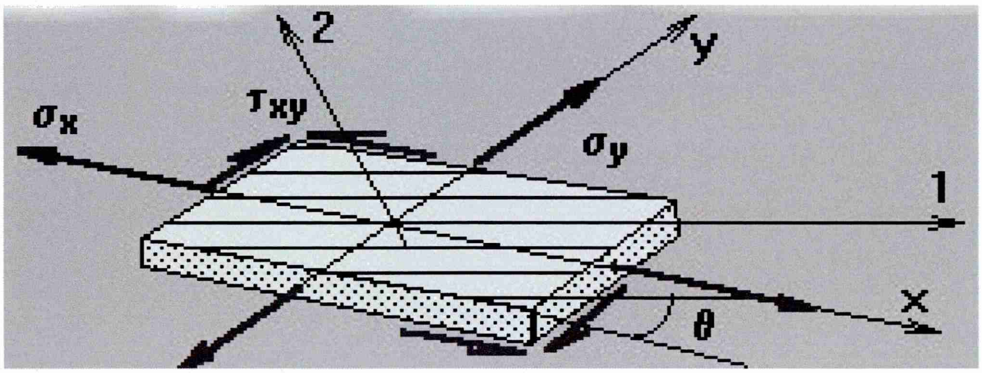


Figure 27. Mechanics Of Composite Materials (Clyne 2013).

The matrix in equation 2 σ1, σ2 and τ12 equal:

$\sigma 1 = \cos 2\Theta \ \sigma x + \sin^2 \Theta \ \sigma y + 2\cos \Theta \sin \Theta \ \tau xy$

$\sigma 2 = \sin 2 \Theta \ \sigma x + \cos^2 \Theta \ \sigma y - 2\cos \Theta \sin \Theta \ \tau xy$

$\tau 12 = (-\cos \Theta \sin \Theta \ \sigma x) + (\cos \Theta \sin \Theta \ \sigma y) + (\cos 2 \Theta - \sin 2 \Theta \ \tau xy)$

Equation 3: expanded matrices.

Due to the forces only being applied in the x direction anything with a y component can be eliminated from the equation which would result in σ1, σ2 and τ12 equalling:

$\sigma 1 = \cos^2\Theta \ \sigma x$

$\sigma 2 = \sin^2 \Theta \ \sigma x$

$\tau 12 = -2\sin \Theta \ \sigma x$

Equation 4: expanded matrices eliminating y component.

With any given angle and a UTS value of 902.4MPa using equation 1 $\sigma 1$, $\sigma 2$ and $\tau 12$ equals:

$\sigma 1 = \cos^2 30 \times (902.4)$

$\sigma 2 = \sin^2 30 \times (902.4)$

$\tau 12 = (-\cos \Theta \sin \Theta) \times 902.4)$

With σx being 902.4 MPa and knowing that there are no forces acting in the σy direction, a Mohr`s circle can be created to better evaluate the forces of $\sigma 1$ $\sigma 2$ and $\tau 12$ at various angles. With $\sigma y$ equalling 0MPa and $\sigma x$ equalling 902.4MPa, R would be equal to 451.2MPa, thus the Mohr`s circle can be plotted & the results tabulated.

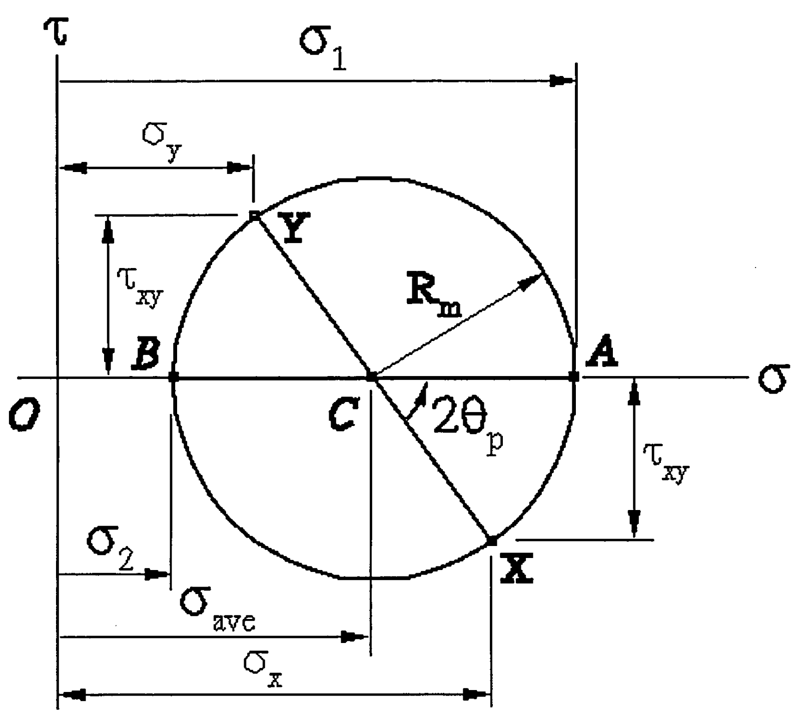


Figure 28: Mohr's Circle For 2D Stress Analysis (Engapplets 2013).

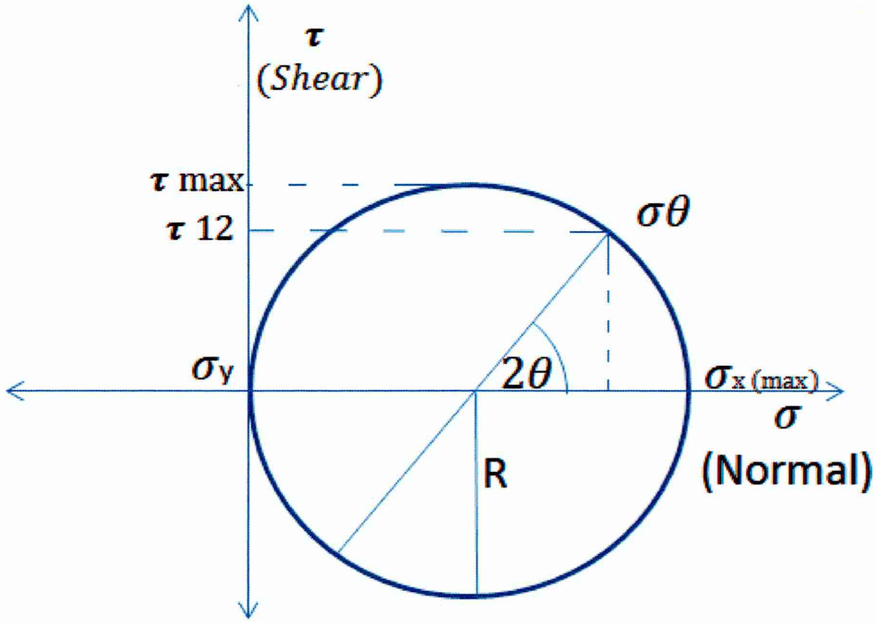


Figure 29: Mohr's Circle For When No Stress Appears In The Y Direction

When σx is equal to 902.4MPa, and process this through both the equations above and Mohr's Circle the failure force can be calculated for the single ply when the fibre reinforcement is at varying angles. The angle mentioned in table 2 below is the angle at which the fibre is off axis to the direction the force is being applied in.

Table 2. Halpin Tsai Equation And Mohr's Circle Results.

Angle from inline fibres	**σ1 (Mpa)**	**σ2 (Mpa)**	**τ12 (Mpa)**
0	902.4	0	0
5	895.5	6.9	78.3
10	875.2	27.2	154.3
15	842.0	60.4	225.6
20	796.8	105.6	290.0
25	741.2	161.2	345.6
30	676.8	225.6	390.8
35	605.5	605.5	423.7
40	529.6	372.8	444.3
45	451.2	451.2	451.2
50	372.9	529.5	444.3
55	296.9	605.5	424.0
60	225.6	676.8	390.8
65	161.2	741.2	345.6
70	105.6	796.8	290.0
75	60.4	842.0	225.6
80	27.2	875.2	154.3
85	6.9	895.5	78.4
90	0.0	902.4	0.0

Using the failure force in table 2 the author can then convert it into a failure load by taking the width and thickness of sample as shown in table 3. The thickness of a single ply is 0.26mm, and the sample width of a tensile testing sample is 12.5mm, therefore the cross sectional area would be 3.25mm^2 which would result in the following failure forces in the σ1, σ2 and τ12 directions:

Table 3. Halpin Tsai Equation And Mohr's Circle Results With Failure Force Conversion With 3.25mm^2 Cross Sectional Area.

Angle from inline fibres	σ1 (Mpa)	σ2 (Mpa)	τ12 (Mpa)	Failure force per ply σ1	Failure force per ply σ2	Failure force per ply τ12
0	902.4	0	0	2932.80	0.00	0.00
5	895.5	6.9	78.3	3313.52	25.36	289.89
10	875.2	27.2	154.3	3238.20	100.68	570.98
15	842.0	60.4	225.6	3115.22	223.66	834.72
20	796.8	105.6	290.0	2948.31	390.57	1073.09
25	741.2	161.2	345.6	2742.54	596.34	1278.86
30	676.8	225.6	390.8	2504.16	834.72	1445.78
35	605.5	605.5	423.7	2240.42	2240.42	1567.87
40	529.6	372.8	444.3	1959.34	1379.54	1644.08
45	451.2	451.2	451.2	1669.44	1669.44	1669.44
50	372.9	529.5	444.3	1379.55	1959.33	1644.08
55	296.9	605.5	424.0	1098.46	2240.42	1568.76
60	225.6	676.8	390.8	834.72	2504.16	1445.78
65	161.2	741.2	345.6	596.35	2742.53	1278.87
70	105.6	796.8	290.0	390.58	2948.30	1073.10
75	60.4	842.0	225.6	223.66	3115.22	834.72
80	27.2	875.2	154.3	100.68	3238.20	570.99
85	6.9	895.5	78.4	25.36	3313.52	289.90
90	0.0	902.4	0.0	0.00	3338.88	0.00

Given this information the author can begin to stack up a laminate and evaluate the theoretical failure force with the practical failure force to determine if this mathematical model can be used to determine the laminate layup required to replace structural steel in various applications.

When a laminate stack up is produced it is important to bear in mind that the laminate must be symmetrical about the neutral axis so as not to cause any undue stresses within the material or warping of the laminate during solidification of the composite.

For example forming a 5 ply and 6 ply laminate stack up, ensuring the layers were equally spaced with equal angles between the layers and mirrored about a neutral axis would result in the following orientations:

5 Ply; 90, 30, -30, 30, 90

6 Ply 90, 30, -30, -30, 30, 90

This would result in the laminate stack ups having a failure load of:

5 Ply = (2932.8+834.7+834.7+834.7+2932.8) = 8,369.7N

6 Ply = (2932.8+834.7+834.7+834.7+834.7+2932.8) = 9,204.4N

Each of these orientations was tested and an average of results was taken. The results showed that a 5 ply laminate with the same orientation mentioned above had a failure load of 6243.1N whereas the 6 ply laminate had an average failure load of 7553.56.

The practical results fall short of the theoretical results by 25.4% and 17.9% respectively. This could be due to the failure mode not being solely the force in the σ x direction but could in fact be caused in part to a portion of shear force acting upon each off axis layer.

For this reason sample testing will be required to find an appropriate laminate stack up as opposed to using the mathematical model.

Chapter 3 – Material Substitution Testing.
3.1 - Steel Testing

Nissan Motoring U.K expressed an interest in the project and its potential ability to produce a new material at mass production rates to reduce the mass of the vehicle. They donated 3 pre pressed blanks of the components they would initially like to replace along with the finished pressed components, these were; the front wing (figure 30), the roof panel (figure 31) and the spare wheel well (figure 32) of the Nissan Qashqai, with the potential of also replacing the side frame of the vehicle (also known as the A-post and B-post) (noting that the side frame material was the same material used for the roof panel). The specification sheets for these panels can be found in Appendix 3. Nissan stated they would be interested in future machine sales if the machine could produce a suitable material to match or improve the mechanical properties of the panels mentioned above, while reducing the mass of each individual component. They added that thickness at this stage was not an issue, as a replacement light weight thermoplastic material would have a much lower Young's Modulus therefore would result in a thicker replacement component than the steel panels currently used.

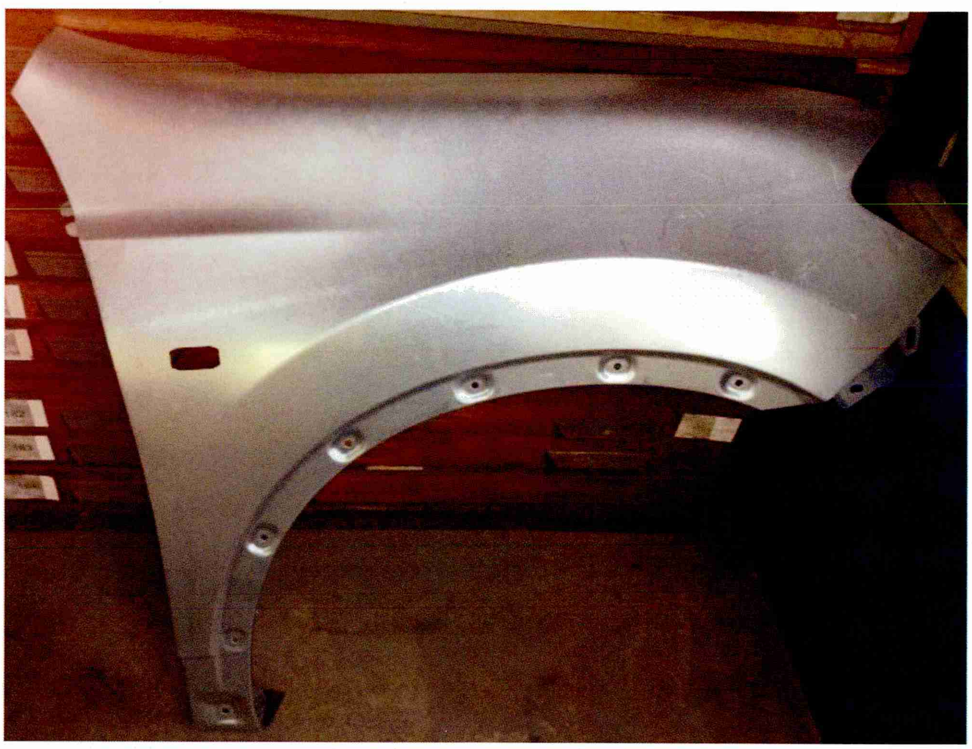


Figure 30: Front Wing Panel Of A Nissan Qashqai.

Figure 31: Roof Panel Of A Nissan Qashqai.

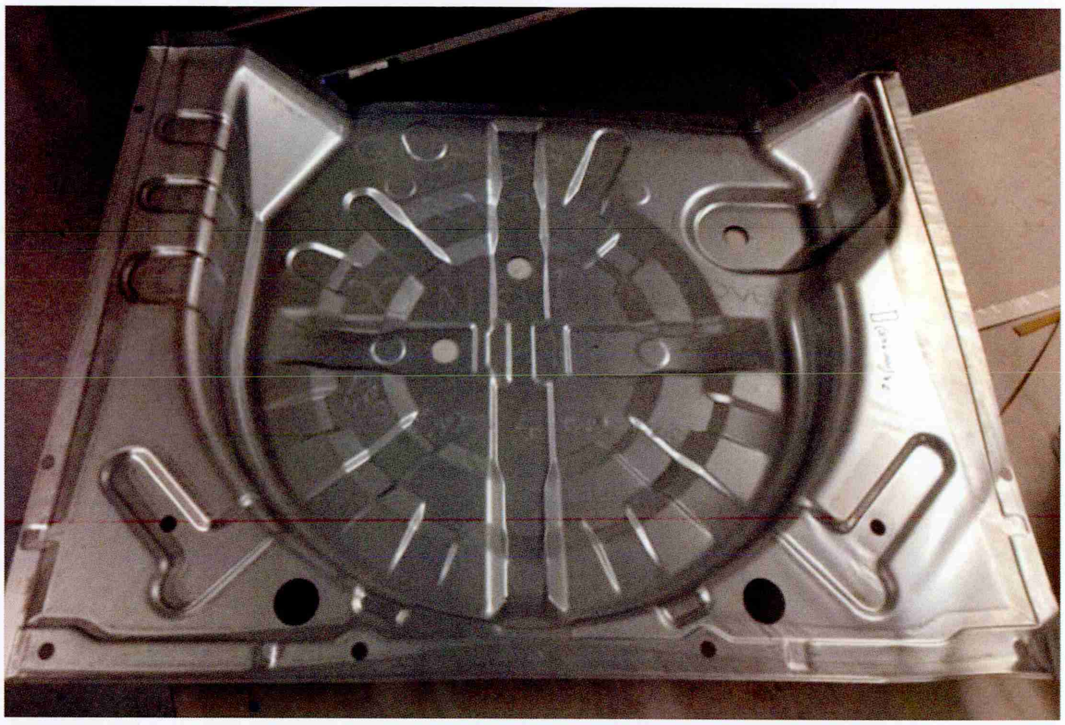


Figure 32: Spare Wheel Well Of A Nissan Qashqai.

From these data sheets we noted the component mass, the UTS of the material, and the overall dimensions. These were then tabulated as shown in table 4 below.

Table 4: Nissan Motoring UK Panel Specifications

Panel I.D.	U.T.S. (Mpa)	Overall dimensions	Component mass (Kg)
Spare wheel well	280	952 x 1133	4.37
front wing	340	1184 x 1223	2.6
glass roof	280	935 x 1333	4.53
side frame	280	3095 x 1528	11.6

Each of these panels was tested in tensile and 3 point bend on an Instron 3367 testing machine (figure 33 and 34) and the impact testing was conducted on an Instron Dynatup testing machine (figure 35). The tensile and 3 point bend tests are important when determining a replacement material for the spare wheel well as the component in the vehicle will experience tensile loads and 3 point bend loads, through adding mass such as shopping to the spare wheel well. Meanwhile the impact test data is important for every component in the vehicle in the event of a collision.

Tensile Testing procedure:

The tensile testing samples were cut out in a dog bone shape with a mid-sample width of 25mm. 5 samples were cut and tested for each panel to get a good average result. The samples were loaded into the gripping clamps of the testing machine (figure 33) ensuring that the top and bottom of the sample was secured tightly in place. The testing machine was balanced before each test to take up the slack in the sample, after which the testing could begin. The machine pulled the sample in tension at a rate of 10mm/min until the sample had failed. The results were recorded for evaluation and tabulating. The testing was repeated until all samples had been tested and a good average could be taken, figure 34 below shows the tensile testing samples after testing.

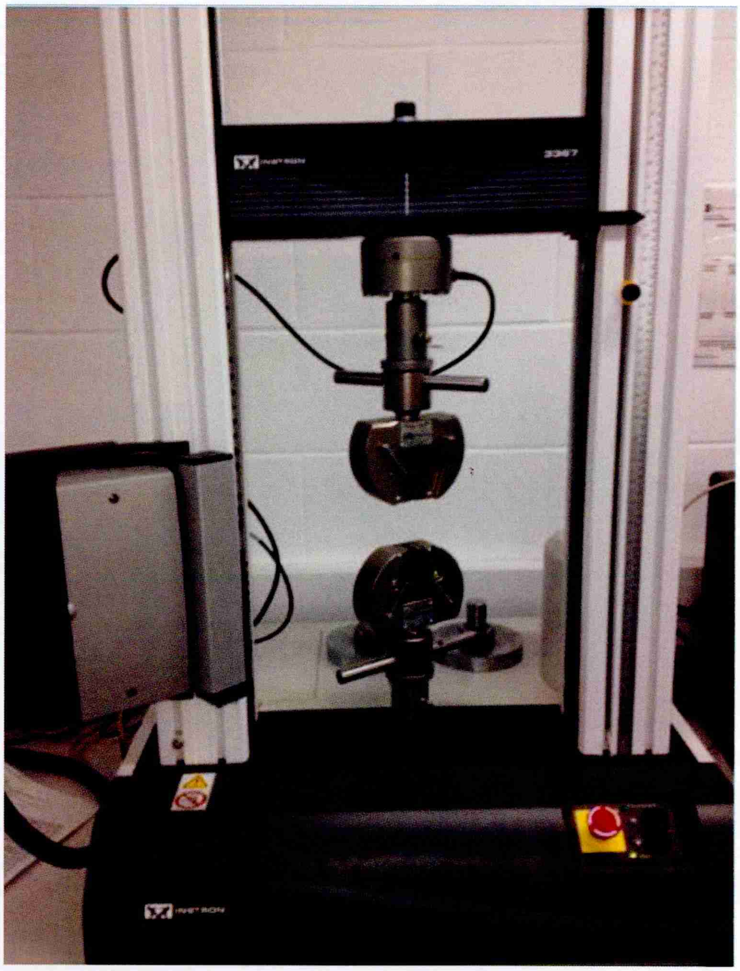


Figure 33: Instron 3367 Testing Machine With Tensile Testing Rig.

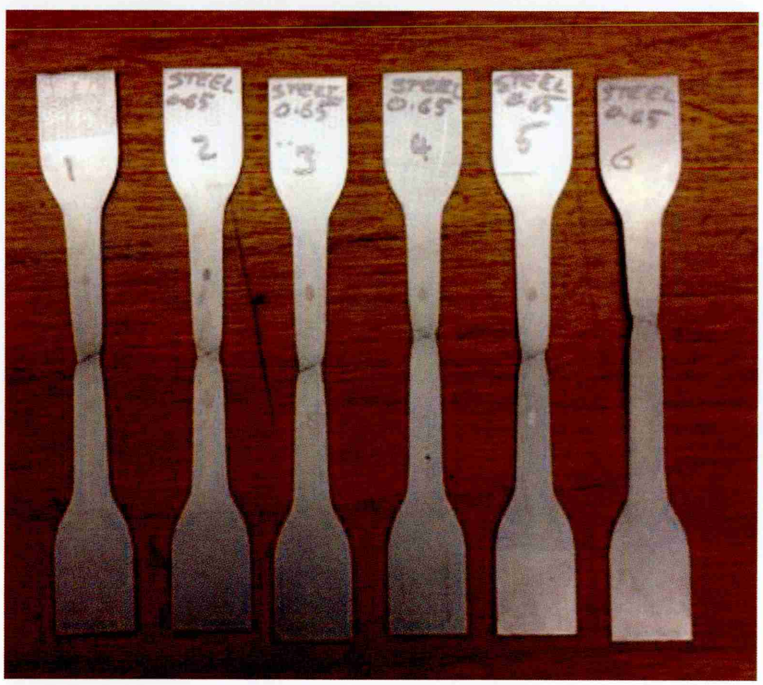


Figure 34: Tensile Testing Samples Post Testing.

3 Point Bend Testing procedure:

The 3 point bend samples were cut into rectangles of 50mm x 20mm. There were 5 samples cut per steel panel. These samples were placed into the 3 point bend testing rig of the Instron 3367 testing machine. The samples were placed with the middle finger on the testing rig positioned in the middle of the sample. The middle finger was lowered down using the inch command on the machine until there was no allowable movement of the sample by hand, this was to take up any slack in the sample. The machine was then balanced so the load was set to zero, after which the test could begin. The samples were displaced at a rate of 10mm/min by the middle finger until the sample failed. The results were then tabulated, averaged per sample and evaluated. Figure 35 and 36 below show the Instron 3367 with the 3 point bend testing rig, and the 3 point bend samples pre and post testing.

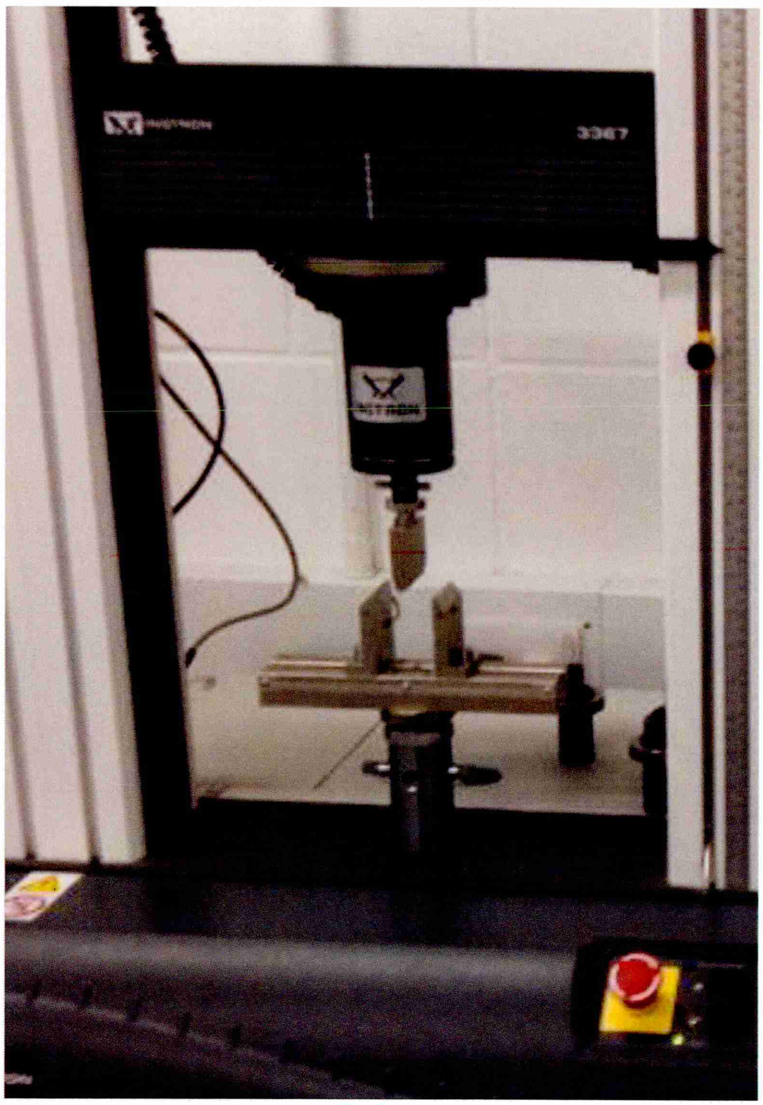


Figure 35: Instron 3367 Testing Machine With 3 Point Bend Testing Rig.

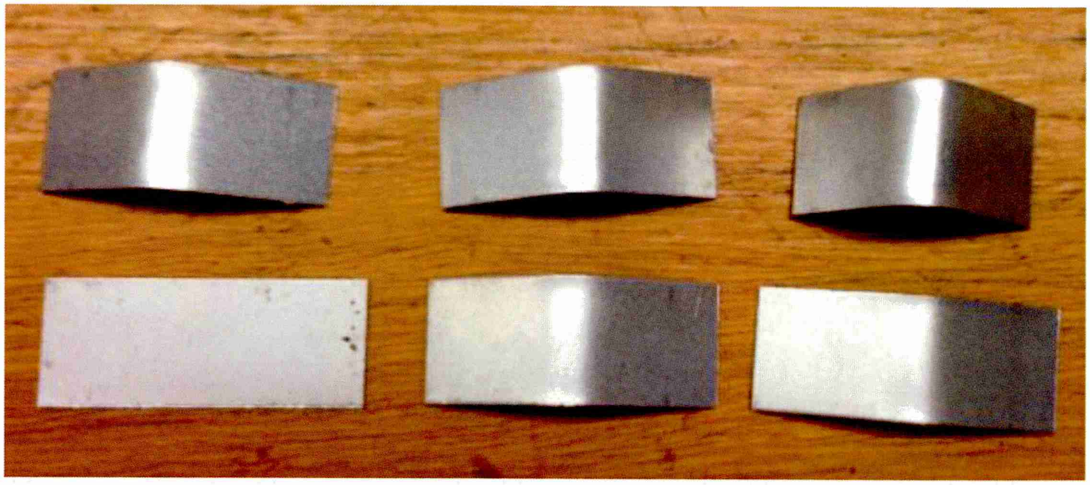


Figure 36: 3 Point Bend Samples Post Testing With 1 Sample Pre Testing (bottom left)

Impact Testing procedure:

For impact testing, the steel panel for the boot pan was cut into 18 round discs of 40mm diameter. Nissan Motoring UK only provided enough steel to test the spare wheel well in impact testing so this shall be used as the bench mark for impact testing. These samples were then loaded into the Instron Dynatup testing machine (figure 37) with the round disc concentric with both the tup and the test rig. The tup was raised to a nominal height of 200mm, and released to fall under gravity until it impacted the sample. The sample was then inspected for damage, with any sign of plastic deformation resulting in a failed sample. The load, force and energy were recorded per sample. The height the tup was raised by was reduced and the sample repeated. This test procedure was repeated lowering the height the tup was raised per sample until a sample did not experience plastic deformation. All but 1 sample failed testing, showing visible signs of plastic deformation as shown in figure 38, the only sample which passed the impact testing is located at the top left hand side of figure 38, and experienced a load of 406N.

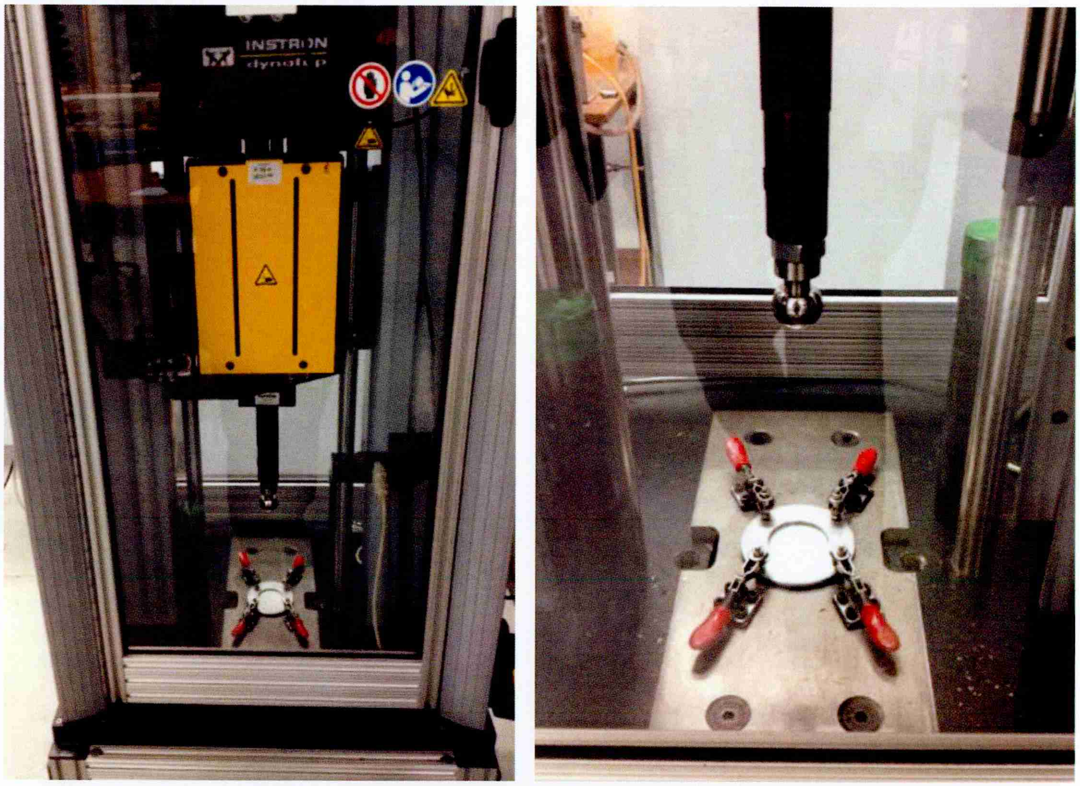


Figure 37: Instron Dynatup Impact Testing Machine With Impact Testing Rig.

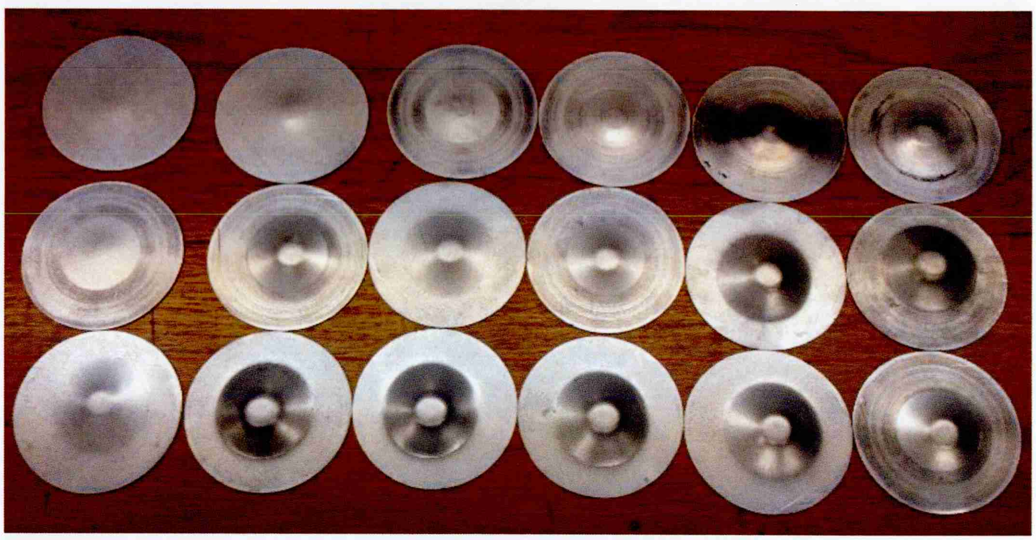


Figure 38: Spare Wheel Well Impact Testing samples.

The average results from all 3 tests can be seen below in table 5. Due to the composite material having a lower tensile strength as described in the Literature review, of 902.4Mpa compared to the steel UTS of 1750Mpa, the results will be converted into a failure load per sample, as this will allow us to directly compare the steel samples with the composite samples, regardless of thickness.

Table 5: Failure Load In Tensile And 3 Point Bend For Nissan Panels.

Tensile Testing	
Sample I.D.	**Average Failure load (N)**
Spare wheel well	1478
Front Wing	2194
Glass roof	2003

3 point bend	
Sample I.D.	**Average Failure load (N)**
Spare wheel well	86.5
Front Wing	102.3
Glass roof	86.4

Impact Testing	
Sample I.D.	**Peak load (N)**
Spare wheel well	406

As can be seen from table 5 the tensile testing failure load of the spare wheel well, front wing and glass roof is 1478N, 2194N and 2003N respectively, the failure load in 3 point bending is 86.5N, 102.3N and 86.4N respectively and the impact testing Peak load is 406N. This tells us that the replacement composite material must have a minimum failure load greater than 2194N in tensile, 102.3N in 3 point bend and a peak load greater than 406N in addition to having less mass than the current steel component. For this reason the fewer layers the component has the greater the mass saving will be without producing a weaker component to the steel panels currently used.

3.2 Thermoplastic Test Data:

Testing the thermoplastic samples has two aims. The first is to match or exceed the failure loads of the steel samples whilst maintaining as fewer laminate layers as possible so as to maximise the mass reduction of the component. The second aim is to determine which fibre orientations will allow us to achieve this, and evaluate how the angle of off axis fibre orientation can be produced automatically.

To try and determine the ideal laminate stack up to replace the panels tested in section 3.1 the author tested a vast range of stack ups and orientations with two different materials. Following the literature review the author determined that a continuous length fibre reinforced thermoplastic was the ideal choice of replacement material. This had the benefits of reinforcing the matrix material to give the component strength, while allowing the construction of the laminate to remain ordered giving more accurate mechanical characteristics and further mass reduction over short fibre reinforced thermoplastic materials.

The two materials tested were Plytron, a 60% by weight glass fibre reinforced thermoplastic material, and Celstran, a 70% by weight glass fibre reinforced material.

Each layer of the laminate was cut out from a roll of unidirectional glass fibre reinforced thermoplastic material in the shape of the mould below (figure 39). Once the required layers with varying orientations had been cut out they were placed in the mould in the orientation stack up required, (ensuring the stack up of orientations was symmetrical about the central layer) with a sheet of PTFE on the top and bottom to prevent the sample sticking to the mould. The fibre orientation of each ply was labelled with respect to the direction of the fibres. A sample with fibres running in a truly vertical direction were named 90 degree layers, whereas layers with the fibres running truly horizontal were labelled 0 degrees, with any fibre angle in between this ranging between 0 and 90, and 0 and -90, Where the end of the fibre was in the top right hand quadrant it was labelled a positive angle, and where the end of the fibre was in the bottom right hand quadrant it was labelled a negative angle. Figure 39 below shows an illustration of a laminate stacking sequence (This image is for illustration only and is not the stacking sequence being used in this project).

Figure 39: Thermoplastic Sample Mould

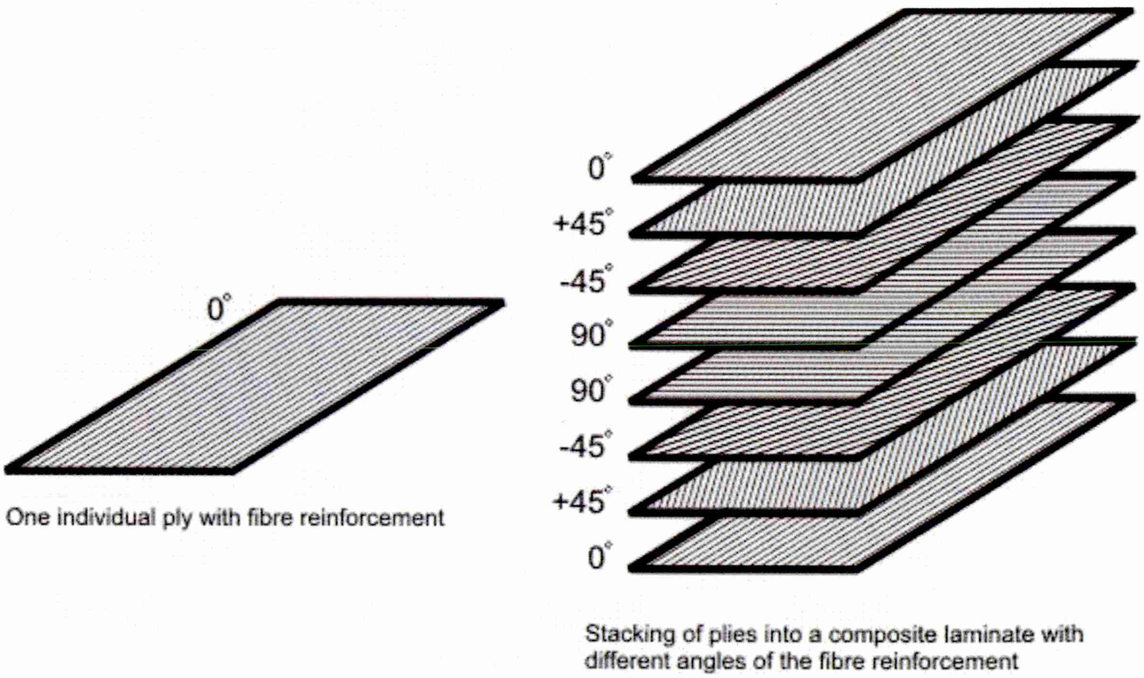


Figure 40: Stacking Sequence Of A Composite Laminate (Composites 2013).

The mould was then placed in a Fontyne Press (figure 41), and heated from ambient temperature to the melting point of the matrix (190°c) and held at temperature for 5 minutes before being water cooled to ambient temperature.

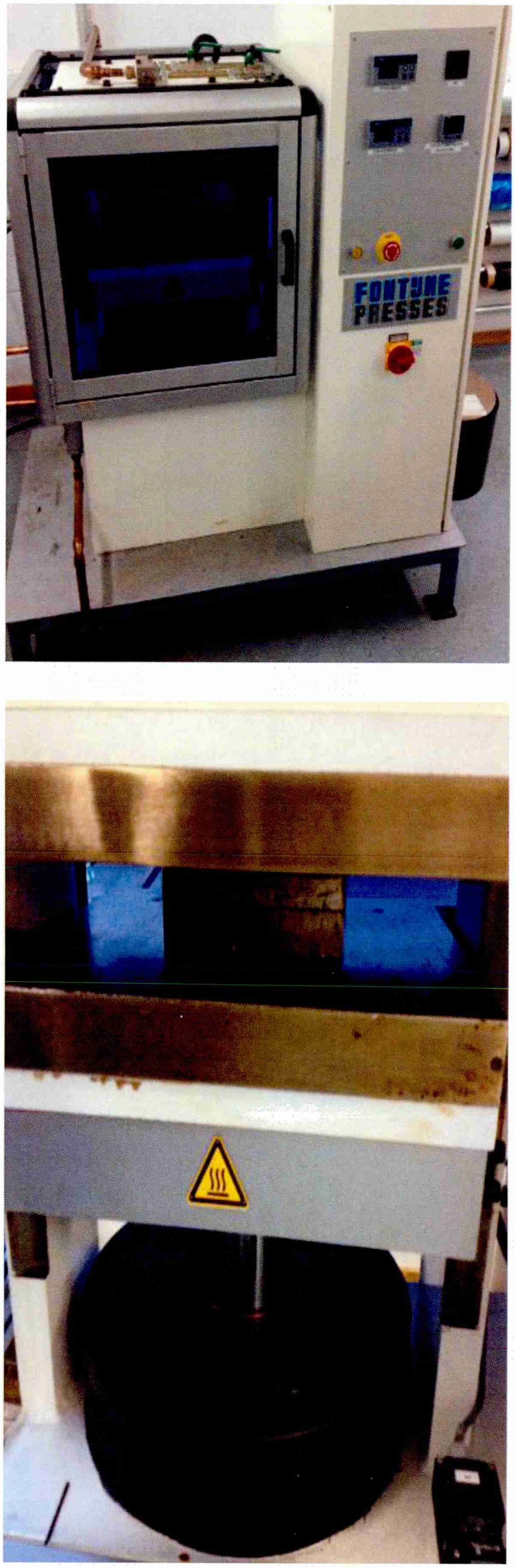


Figure 41: Fontyne Press At Sheffield Hallam Univeristy Composite Lab.

Once the tool had been cooled to ambient temperature it was taken out of the press, and the fully consolidated card was extracted from the mould. Figure 42 below shows a 5 ply consolidated card of Celstran with the fibre orientation 0, 60, -60, 60, 0. A card like this was made for each orientation and each range of tests, for example 1 card would be used to produce 5 tensile testing dog bone samples for tensile testing, 1 card would be used to produce 3 point bend samples in both the horizontal and vertical directions, and many cards were produced for the impact testing samples, with 1 card creating 3 impact testing samples.

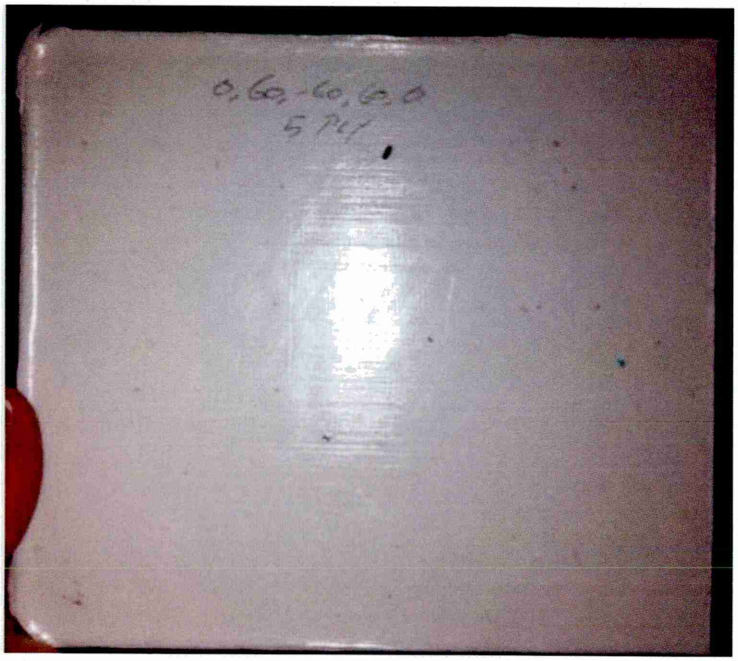


Figure 42: Fully Consolidated Card Of Celstran.

When the cards had been made, the samples were cut out ready for testing and labelled up with their ply, orientation and sample number. These samples were then tested in the appropriate testing machines as per the steel testing samples. The samples were always tested in the laminates' strongest and weakest fibre orientation, that is to say the orientation in which a particular stack up had the fewest or no fibres, for example the laminate with stack up 90,30,-30,30,90 was also tested 90 degrees to that so the fibres were 0,-60,60,-60,0 to determine the failure force of the sample in its weakest orientation.

3.2.1 Plytron Tensile Testing:

The tensile testing samples were placed in the Instron 3367 testing machine with the tensile testing rig, ensuring the samples were gripped sufficiently in the gripping clamps. The samples were then pulled in tension at a rate of 10mm/min until the sample failed, constantly recording the force and extension of the sample. This was repeated four times and the results were averaged then tabulated for evaluation and comparision against other orientations and stack ups.

Plytron was the first material to be tested as that was the material which was delivered weeks before Celstran was delivered. The average result for each laminate and its fibre orientation is given below.

Table 6: Plytron Tensile Testing Results Average Failure Load.

Tensile Testing		
Plytron (60% by weight glass fibre)		
Sample Ply	**Sample Orientation**	**Average Failure Load (N)**
9	0,45,90,-45,0,-45,90,45,0	6467.8
8	90,45,0,-45,-45,0,45,90	5987.7
8	0,90,45,-45,-45,45,90,0	5986.9
8	0,60,-60,0,0,60,-60,0	6076
8	0,45,90,-45,-45,90,45,0	5780.7
7	90,30,-30,90,-30,30,90	6484.6
7	0,60,-60,0,-60,60,0	4160
7	45,-45,45,90,45,-45,45	3262.9
6	90,30,-30,-30,30,90	4541.4
6	0,60,-60,-60,60,0	4431.4
5	90,30,90,-30,90	5730.3
5	0,60,0,-60,0	3233.9
4	90,30,-30,90	3816.4
4	45,-45,45,-45	1459.9
4	0,60,-60,0	2285.86

The results in table 6 above show that the 9 ply through to 5 ply samples had very high failure loads, in excess of 150% of the failure load of the steel samples. The 4 ply sample with a fibre orientation 0,60,-60,0 (the same laminate as the 90,30,-30,90 but perpendicular testing direction) would be a suitable replacement for the boot floor, roof panel and front wing of the Nissan Qashqai with a failure load of 2285.86N which is just above the 2194N.

The density of Plytron is 1.5g/cm^3 from the data sheet in appendix 1 with a ply thickness of 0.27mm. A 1m^2 sheet of material has a volume of 100 x 100 x 0.027 = 270cm^3 which gives a mass of 405g per ply. From this a 4 ply laminate would have a mass of 1.620Kg per m^2 which is a vast mass reduction compared to the 4.37Kg and 4.53Kg mass of the spare wheel well and glass roof respectively.

The end component must be less than 3.6Kg per m^2, which eliminates the 8 ply and 9 ply samples as they weigh 3.24Kg, and 3.645Kg respectively. For this reason the 8 ply and 9 ply orientations were eliminated from the 3 point bend tests.

3.2.2 Plytron 3 Point Bend:

The 3 point bend test samples were placed in the Instron 3367 testing machine with the 3 point bend testing rig, ensuring the samples were placed with the middle finger of the rig positioned in the middle of the sample. The middle finger of the rig was lowered slowly using the jog function until the finger touched the sample and the sample could not be moved, this was done to take up any of the slack. The samples were then subjected to 3 point bending with the middle finger displacing the sample at a rate of 10mm/min until the sample failed, constantly recording the force and extension of the sample. This was repeated four times and the results were averaged then tabulated for evaluation and comparision against other orientations and stack ups.

The results from the 3 point bend tests below in table 7 indicate that the failure load in the laminate's weakest orientation for 4 and 5 ply is well below the 102.3N required to replace the steel components. There is a vast jump from the 5 ply results to the 6 ply results with the failure load in 6 ply being 242N which is far in excess of the 102.3N required. Looking at the 6 ply tensile testing results the failure load is 4431N which is more than double the 2194N failure load required, resulting in an end component which far exceeds steel in tensile testing and 3 point bend testing.

Table 7: Plytron 3 Point Bend Results Average Failure Load.

3 Point Bend Testing		
Plytron (60% by weight glass fibre)		
Sample Ply	**Sample Orientation**	**Average Failure Load (N)**
4	0,60,-60,0	25.74
5	0,60,-60,60,0	44.4
6	0,60,-60,60,0	242
7	0,60,-60,60,-60,60,0	364

3.2.3 Celstran Tensile Testing:

The Celstran tensile tests were tested in exactly the same manner as the Plytron and steel tensile tests. Comparing Celstran and Plytron, Celstran has a higher fibre volume of 70% glass fibre by weight compared to Plytron which has only 60%. Using Celstran instead of Plytron may allow us to reduce the number of layers in the laminate, further reducing the component mass, or offer a finished component with even greater mechanical properties over those offered by Plytron.

Celstran was tested in 4 ply, 5 ply and 6 ply as shown below to determine if Celstran could offer a component with fewer layers. Table 8 shows that 4 ply Celstran would be a suitable replacement for the steel components with 5 ply and 6 ply having failure loads far in excess of steel samples tested.

Table 8: Celstran Tensile Testing Results Average Failure Load.

Tensile Testing		
Celstran (70% by weight glass fibre)		
Sample Ply	**Sample Orientation**	**Average Failure Load (N)**
4	0,60,-60,0	2339.8
5	0,60,-60,60,0	3398.6
6	0,60,-60,-60,60,0	5237

3.2.4 Celstran 3 Point Bend:

The Celstran 3 point bend tests were carried out in exactly the same manner as the Plytron and steel 3 point bend tests. The results in table 9 for the 3 point bending samples indicate that a 4 ply laminate would not be a suitable replacement, whereas the 5 ply laminate would with a failure load of 126.6N. Tables 8 and 9 show that 5 ply Celstran with the fibre orientation 0,60,-60,60,0 (also known as 90,30,-30,30,90) can be used as a suitable replacement for the steel samples tested in section 3.1.

Table 9: Celstran 3 Point Bending Results Average Failure Load

3 Point Bend Testing		
Celstran (70% by weight glass fibre)		
Sample ply	**Sample Orientation**	**Average Failure Load (N)**
4	0,60,-60,0	31.9
5	0,60,-60,60,0	126.6
6	0,60,-60,60,0	292.7

By using Celstran instead of Plytron the author reduced the laminate stack up by 1 layer. Celstran has a mass of 435g/m^2 as shown on the data sheet in appendix 2, the stack up would be 2.175Kg compared to the 2.43Kg of 6 ply Plytron providing a further mass reduction of 255g per m^2.

As the 5 ply sample of Celstran was chosen as the replacement material, impact tests were conducted on the 5 ply laminate with the fibre orientation 0,60,-60,60,0 to determine whether it could withstand a greater impact load than the steel samples. As shown in table 10, the peak load of the 5 ply Celstran laminate was 5537N, which is far in excess of the steel sample with only 406N. This indicates that the Celstran 5 ply laminate can withstand 13.6 times the impact load of the steel samples tested.

Table 10: Celstran Impact Testing Results.

Impact Testing	
Sample I.D.	**Peak Load (N)**
5 Ply Celstran 0,60,-60,60,0	5537

Chapter 4 – Feasibility Study

Before the project continues any further the author must determine whether achieving off axis laminates is feasible and commercially exploitable at mass production rates.

4.1 Required Production Rate:

Firstly the author must determine what production rate is required to reach the volumes required by a mass production automotive manufacturer, compare that against what is achievable, and determine whether the cost to achieve such volumes is acceptable or not. In addition to this it must determined if the width of material required can be achieved at a high speed or not.

From section 3.2 it was determined that a 5 ply laminate of Celstran with the fibre orientations 0,60,-60,60,0 would be a suitable replacement for the steel components, this fibre orientation when rotated through 90 degrees becomes 90,30,-30,30,90 for exactly the same laminate, this laminate can also be expressed as 30,-30,90,-30,30 by rotating through a further 60 degrees. Given that the fibre orientations 90, 30 and -30 must be achieved to produce this laminate the author must think of a way to produce them automatically. The material is supplied with the continuous length fibres naturally in the 90 degree orientation, which only leaves the 30 degree and -30 degree orientation to produce.

A 30 degree and -30 degree sample can be produced by wrapping the material around a mandrel as described in the literature review and compressing it to produce a 2 ply material with fibres running in both the 30 degree and -30 degree orientations simultaneously.

The 5 ply laminate required can therefore be produced with a single 90 degree layer, sandwiched in between a top and bottom double layer of 30 and-30 degrees fibre orientation.

The automotive industry mostly uses materials up to a width of 1m, so our replacement material must be 1m wide to service the mass production market.

Production volumes of the Nissan Qashqai are 280,000 per year; working on the basis of a 49 week production year, running 8 hours a day, 5 days a week this equates to 1960 production hours a year. 1960 production hours equates to 7,056,000 production seconds a year, thus dividing this value by the production volume required, the prototype machine must produce 1 sheet of 5 ply material every 25 seconds.

To produce the 1m wide sheet of 2 ply material from a mandrel the mandrel needs to have a circumference of 2000mm, therefore a diameter of 636.6mm. The tape must wrap around the mandrel at 30 degrees and be joined to form a continuous tube. Therefore Dm = 636.6 and $\theta = 30$

To determine the input tape width (Wt) required and the production rate (VL) the following equations must be used;

Tape width (Wt),

$Wt = \sin\theta \times \pi \times Dm$ ....(Equation 5)

$= \sin 30 \times \pi \times 636.6 = 1000$

Production rate (VL),

$VL = \sin \theta \times Vt$ ....(Equation 6)

$= \sin 30 \times Vt$

$= 0.5 \times Vt$

The input tape width required to produce this would need to be 1000mm as shown in the equation above. After contacting Ticona who manufacture Celstran, they can provide rolls of tape with a width of 13.5". The 1000mm sheets can be produced by joining 3 rolls of 13.5" (343mm) wide tape together which Celstran can provide. This tape width would allow each roll of tape to have a 10mm overlap for joining, which would create a final tape width of 1009mm to wrap around the mandrel and join.

4.2 Thermoplastic Welding:

There are many ways of joining the material with a polypropylene matrix such as ultrasonic welding, laser welding, hot air welding, welding using molten polypropylene and adhesive bonding.

The use of a molten polypropylene weld was ruled out as it would add more mass per laminate layer. Adhesive bonding was also ruled out due to the high costs of the adhesive, the inability of an adhesive to be recycled or reformed and the addition of mass to the component. For these reasons a welding method which utilised the thermoplastic matrix as a form of bonding the sheets together was the preferred choice, for example the ultrasonic, laser and hot air welding processes which do not add material to the laminate.

4.2.1 Laser welding:

The laser welding was investigated with a company called Laser SOS, who were sent samples of the material to weld. Laser welding uses a powerful laser which is focused on a point of a laser absorbent thermoplastic; this converts the laser into heat energy, melting the thermoplastic, which joins under the application of an external force to produce a strong weld. Figure 43 shows a laser welding process like that used to laser weld thermoplastics.

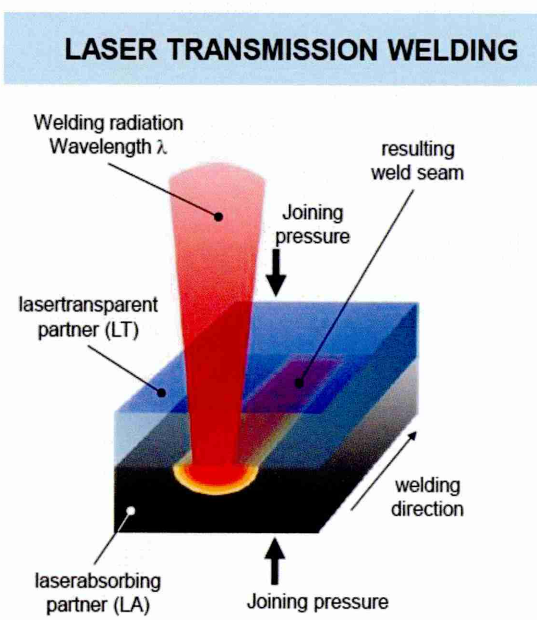


Figure 43: Laser Transmission Welding (Optics 2013).

The feedback received from Laser SOS was that the power of the laser was too intense for the material, as such it wilted under the application of a laser. This ruled out using a laser to weld the material.

4.2.2 Ultrasonic welding:

Samples of the thermoplastic material were sent to three companies to conduct trials to determine the achievable speeds. These companies were JSK Ultrasonics, Pfaff and Southfork Innovations. There are two distinctive types of ultrasonic weld: continuous ultrasonic welds, and staking welds. The continuous ultrasonic welds are performed through a rotating wheel which is constantly in contact with the material as shown in figure 44, whereas the staking method is a static weld which involves the horn of the welding equipment coming into contact with a specific spot on the material and performing the weld as shown in figure 45. The prototype machine requires a continuous weld to be able to join the material at mass production rates.

Ultrasonic welding of thermoplastics uses a horn which vibrates at the natural oscillating frequency of the matrix in the composite material. This excites the molecules causing them to heat up and melt allowing a weld to be formed. The frequency from the horn is echoed off the anvil, back into the thermoplastic to encourage excitement of the molecules.

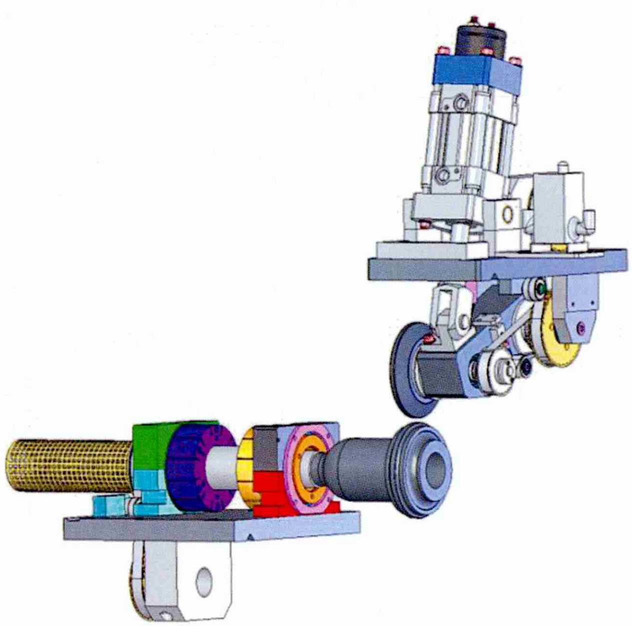


Figure 44: Continuous Ultrasonic Welding Equipment (Mecasonic 2013).

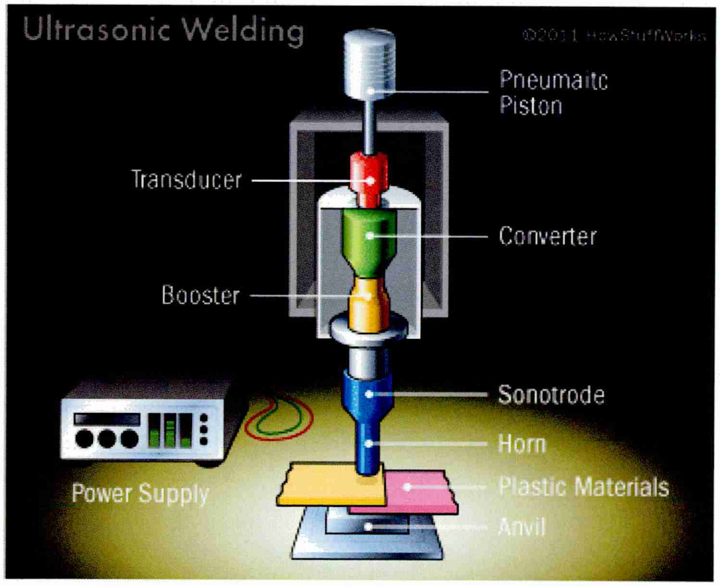


Figure 45: Static Ultrasonic Welding Equipment (How Stuff Works 2013).

The feedback from JSK Ultrasonics, Pfaff and Southfork innovations all concluded that the material could be welded using a continuous weld, but only up to 15m/min linear speed. After this speed the quality of the weld was insufficient for use in a manufacturing process.

4.2.3 Hot Air Welding:

Hot air welding uses an industrial hot air welder (much like an industrial hair dryer) to melt the matrix material with a focused outlet point and fuse it together using rollers situated directly behind the heat source. The heat from the hot air welder is focused on the top surface of the bottom layer of material and the bottom surface of the top layer of material, softening the two surfaces which become tacky as they melt. The material is then compressed through nip rollers directly behind the heat source to force the material together and form a strong weld. Pfaff, one of the companies which conducted the ultrasonic welding trials, also conducted the trials on their range of hot air welding machines, and were pleased to inform us that using a hot air welding machine allowed us to achieve an excellent weld at speeds of 40m/min. this was far in excess of the speeds achievable through ultrasonic welding.

The welding trials have proven that Celstran can be welded sufficiently at speeds of up to 40m/min for hot air welding and 15m/min for ultrasonic welding.

4.3 Production of a 5 ply laminate:

Material with the fibres at 90 degrees can be produced at a rate of 40m/min utilising a welding unit with 2 hot air welding heads to join 3 rolls of thermoplastic material. This widened material would require an overlap of approximately 10mm per weld. When raw material of width 343mm (13.5") is used, a joined material of width 1009mm can be produced which can be utilised to produce the 90 degree layers of the laminate, as well as also being used to form the 30,-30 degree orientation layers when wrapped around a mandrel.

If 3 rolls of material of material are joined to produce a continuous sheet of 1009mm wide tape and wrapped it around a mandrel to produce a double layer of material with the orientation 30,-30 with the same welding equipment used to produce the 90 degree tape, the double layers (30,-30 orientation) of material would be produced at half the rate of the 90 degree layers which is a rate of 20m/min (1 double layer every 3 seconds).

The finished 5 ply laminate would require 2 of the double layers, and a single 90 degree layer which results in a production rate of one 5 ply laminate every 7.5s. These laminate layers can be produced at 30% of the rate of the final production speed required to replace a mass production vehicle panel. This would result in 933,332 laminates per year, assuming machine set up time, and expected down time will be 50% the estimated annual production will be 466,665 laminates per year. These finished layers of material would require part consolidating prior to pressing and forming into a finished panel.

The part consolidation of a 5 ply laminate layer can be done using a static ultrasonic welding unit as shown in figure 45 above. Southfork innovations conducted trials on the staking of 5 layers of material to form a part consolidated laminate. They were able to achieve a satisfactory weld bonding 5 layers of material together in only 2 seconds using a 35mm diameter knurled horn.

4.4 Processing costs:

To produce the 5 ply material the production process will require certain pieces of capital equipment such as a double hot air welding head and a single hot air welding head, as well as 4 static ultrasonic welding units, not to mention numerous fabrications, motors, and control panels.

After contacting Pfaff for a price for the hot air welding equipment, Southfork innovations for a price for the ultrasonic equipment and Peter Anderton, Joseph Rhodes Technical Director for an in house fabrication and build cost for the project, the estimated cost to produce a prototype machine was:

Double hot air welding machine £50,000

Single hot air welding machine £ 25,000

4 x ultrasonic welding equipment £5,000 each

Design, fabrications and materials £90,000

Control panels £30,000

Total project machine costs £215,000

With an estimated machine cost of £215,000, the depreciation over 5 years would result in a cost per laminate of 10.85p per 5 ply meter squared laminate.

Raw material costs:

The cost of Celstran is €7/kg = £5.83 (exchange rate of £=€1.2)

The material has a mass of 435g/m squared therefore 5 layers = 2.175Kg

The raw material cost of a 5 ply m^2 laminate = £12.68

Costs including production costs = £12.79/ laminate material.

4.5 Mass Saving:

The mass saving gained by using a 5 ply laminate over steel components is shown below in table 11. The savings obtained by using a 5 ply laminate of Celstran result in a mass saving in excess of 50.58%. The greatest mass saving was seen in the side frame which had a mass saving of 64% equating to a 7.43Kg reduction in mass.

Table 11: Mass Saving Per Panel

Panel I.D.	Overall Dimensions	Area	Component mass	Composite mass	Mass saving	Mass saving
Spare wheel well	952 x 1133	1.08	4.37	1.81	2.56Kg	58.66%
Front Wing	1184 x 1223	1.45	2.6	1.28	1.32Kg	50.58%
Glass Roof	935 x 1333	1.25	4.53	1.79	2.74Kg	60.50%
Side Frame	3095 x 1528	4.73	11.6	4.17	7.43Kg	64.09%

4.6 Fuel saving:

The automotive industry has to meet a government directive to reduce vehicle carbon emissions to 95g/km or less of CO2 by 2020 (European Commission 2014). By using a 5 ply laminate of Celstran in vehicles, the automotive industry would save a considerable amount of mass, which would result in more efficient vehicles, longer range of the vehicles, and reduced vehicle emissions.

The vehicle mass equates to 56% of the total fuel consumption as shown in figure 46. When one takes the mass and average MPG of a Nissan Qashqai the fuel consumption per Kg of vehicle mass can be calculated as follows:

Vehicle mass – 1356Kg

Average MPG – 34.9 (2.0l model)

Average annual mileage – 8430 miles (Rofique et al 2010).

Litres used per year – 8430/34.9 = 241.55G

Convert gallons into litres – 241.55G = 1,098L used per year.

1,098 x 0.56 = 614.9L used due to mass.

614.9 / 1356 = 0.45L of fuel saved per Kg saved in vehicle mass, per year.

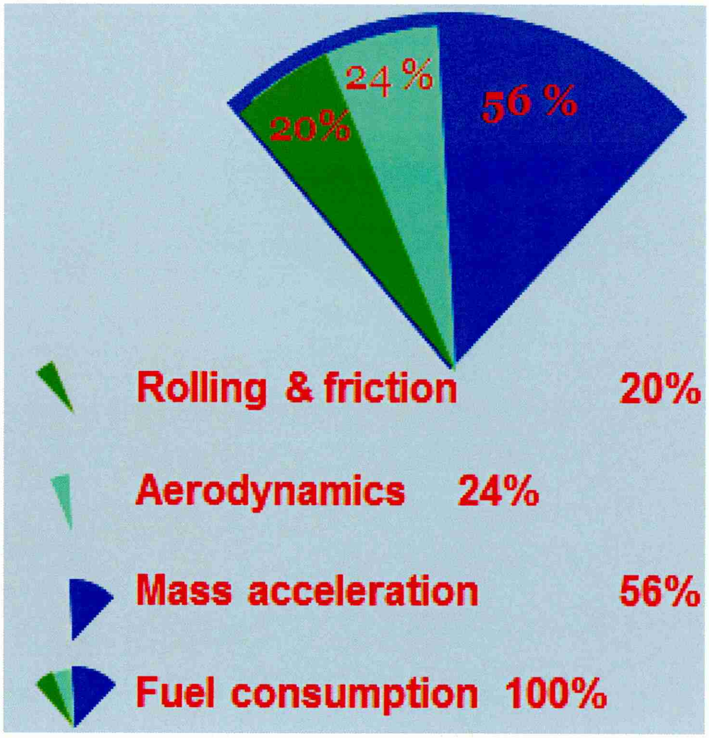


Figure 46: Vehicle Fuel Consumption (Ellis 2011).

4.7 Conclusion of feasibility study:

A material has been sourced (Celstran) which would be a suitable replacement for steel components in vehicles. It has been proven that using a hot air welding process a production speed of up to 40m/min linear speed can be produced which results in an estimated production volume of 466,665 laminates per year. The rolls of Celstran can be joined to form a 1009mm wide roll suitable for tube production. The processing costs are very small at 10.85p/m^2 5 ply laminate, which combined with the raw material price, results in a price of £12.79 to produce a 5 ply laminate, and the use of this material would result in a mass saving in excess of 50.58%. This indicates that the project is feasible.

Chapter 5 – Machine Design – Concepts 1 & 2.

The first step in designing a machine for the production of off axis fibre reinforced thermoplastic material at commercially exploitable production rates is to develop a concept and refine it until a suitable machine design is reached which is cost effective, functions correctly and can be brought to market.

When designing the concept the author validated the use of each process in the machine by testing each process individually and determining if the material acted the way it was expected to.

There were two ways of achieving the end product which resulted in two concept designs being produced. These designs were then pitched to the board of directors at Joseph Rhodes to decide which idea they would like to take forward and manufacture.

5.1 Concept 1 – Off Axis Roll of Material Method:

The machine was developed on a stage by stage basis; the author knew what the desired output of the machine would be from the input material but how this would be achieved was the missing element. The machine was broken down into four stages to produce an off axis laminate composite ready for pressing into the final component. These stages were;

Stage 1 – Material widening.

Stage 2 – Tube forming.

Stage 3 –Part consolidation.

Stage 4 – Full consolidation.

5.1.1 Stage 1 - Production of Wide Material

The author became aware from the feasibility study in section 4 that the tube circumference would have to be 2000mm to achieve a flattened 2 ply sheet with fibres running at an angle equal and opposite to the in line orientation. This would require an input material which was 1000mm wide excluding any overlaps, as detailed in section 4.1. To produce material of this width, 3 rolls of Celstran provided in a width of 343mm must be joined together. This would be achieved by using a welding machine with 2 hot air welding heads to join the material and produce continuous tape 1009mm wide if a 10mm overlap was used, at a rate of 40m/min. Figure 47 below shows the 3 rolls of continuous length material traveling from left to right, being welded by the hot air welding unit in the middle, trimmed to an exact with by the edge trimming unit towards the end of the roll, then collected at the right hand side to form a continuous roll of tape 1009mm wide.

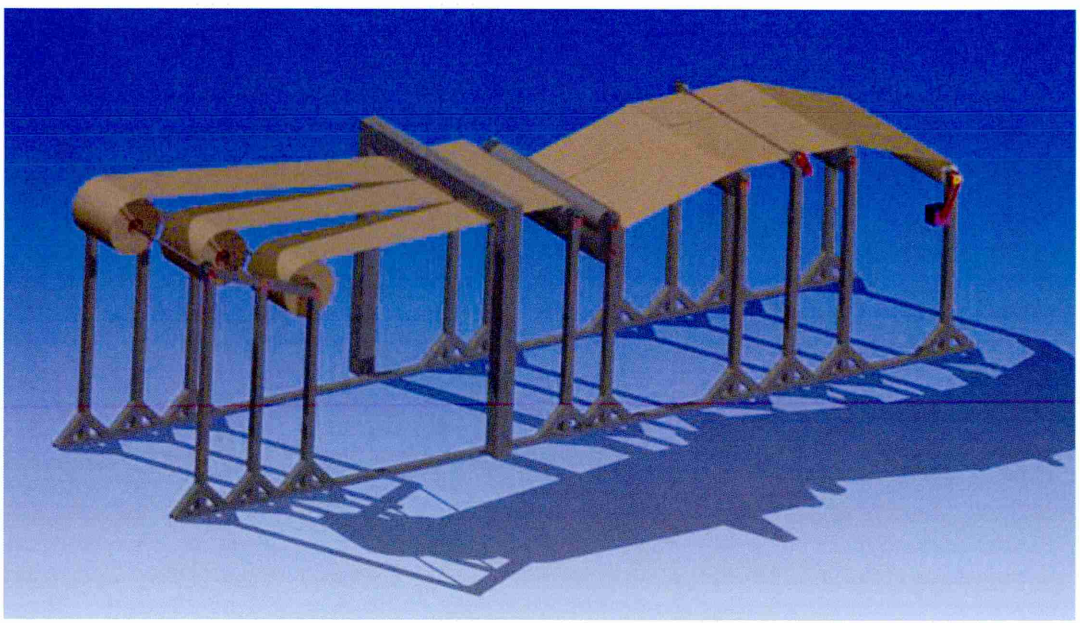


Figure 47: Stage 1 – Material Widening.

The function of stage 1 was validated by conducting trials on welding the material and visually examining the welded material. A weld was achieved at a rate of 40m/min by using a hot air welding system which with a 9mm material overlap produced a sufficient weld.

5.1.2 Stage 2 - Tube Forming

Stage 2 uses the widened material produced in stage 1; this is then wrapped around a mandrel at 30 degrees to form a continuous tube. This tube is joined using a hot air welding machine just like the one used in stage 1 and driven using a belt drive to form a helical weld around the tube. Once the tube has been formed it is then flattened through a set of rotating rollers which rotate at the same rpm as the tube rotates as it is being formed. By flattening the material a 1m wide strip is produceed which has the fibres at +/- 30 degrees to the direction of travel. The flattened material is then collected on a roll which is also rotating at the same speed as the flattening rollers, so the collection rollers and flattening rollers are not rotating with respect to the tube as they are all rotating at the same speed.

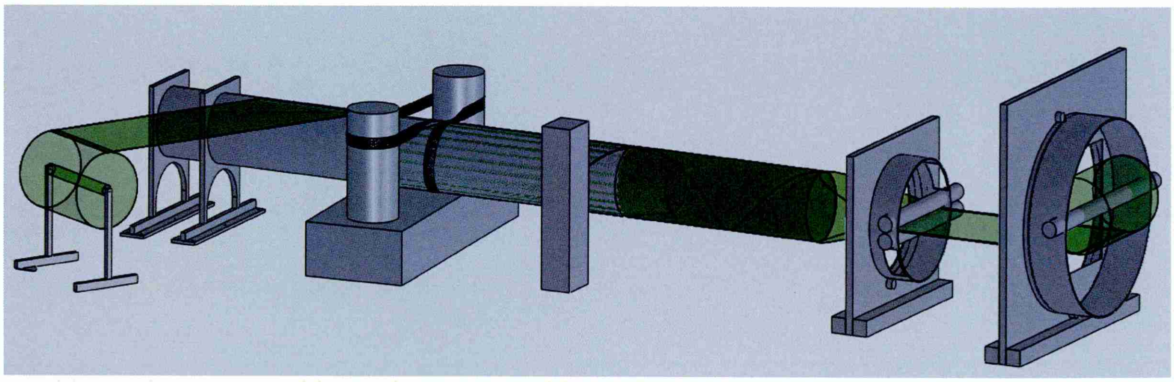


Figure 48: Stage 2 – Tube Forming - Iteration 1.

Developing concept 1 the author managed to reduce the complexity of the back end of stage 2, where the material is flattened, and collected on separate rollers, the two rotating units were merged into one, to form a single rotating body which was required to match the rotational speed of the tube being formed. The belt drive was changed to a more compact one which drove the tube from underneath. Figure 49 below shows the flattening and collection rollers merged into one along with a more compact belt drive positioned under the welding unit.

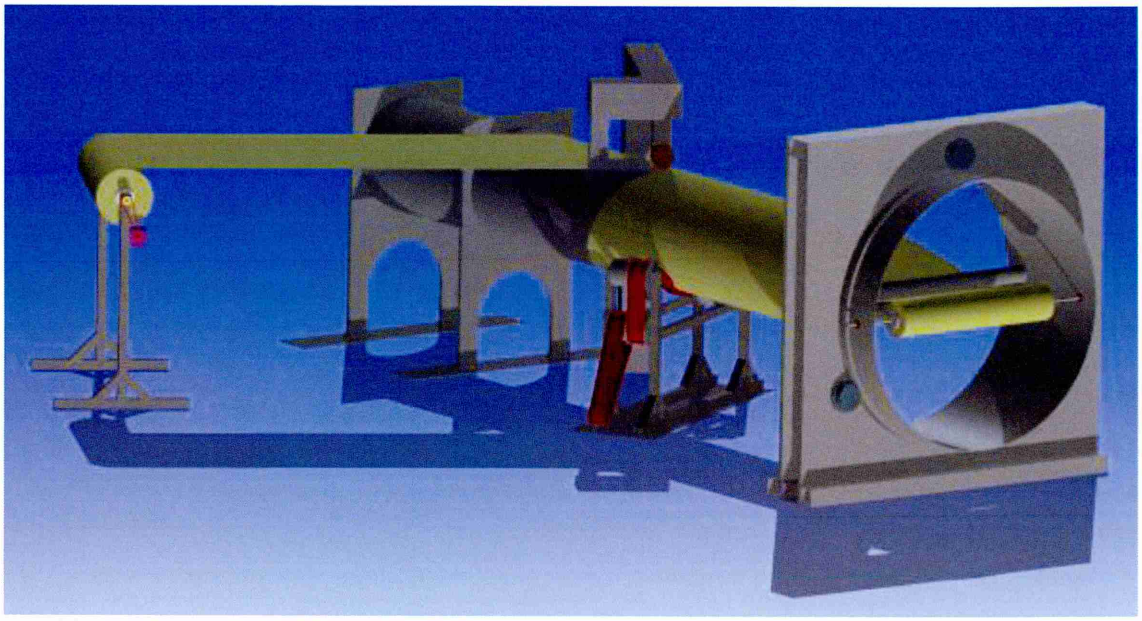


Figure 49: Stage 2 – Tube forming – Iteration 2.

The processes of stage 2 were proven by visual inspection after forming the material around a scale mandrel and performing a helical weld with a heat gun. The continuous tube formed around the scale mandrel was then passed through a set of nip rollers which had a gap twice the material thickness. This gap allowed the material to be passed through whilst snapping the fibres at the edge of the sheet of material. This formed a 2 ply off axis sheet of material.

5.1.3 Stage 3 - Part Consolidation:

Using the continuous length roll of material from stage 1 with fibre orientation 90 degrees, and 2 rolls of flattened material with fibre orientation +/- 30 degrees from stage 2, these can be brought together and staked to form a part consolidated 5 ply sheet of off axis material. Stage 3 brings the rolls of material together with the 2 ply layers from stage 2 on the top and the bottom of the stack up and the roll of material from stage 1 in the middle to produce a laminate with 30,-30,90,-30,30 fibre orientation. These rolls are indexed 250mm and stopped while 2 ultrasonic welders engage the material 250mm in from either side to produce 2 ultrasonic welds (a process known as staking). The material is then indexed a further 500mm and the same weld performed. This produces 4 welds in the part consolidated laminate positioned 250mm from each edge. Once the first sheet has been staked the rollers index and produce the same welds every 500mm. Following this, the now part consolidated continuous off axis material is cut into meter lengths using a travelling shear to produce the meter squared 5 ply part consolidated laminate. Figure 50 below shows the rolls of material being brought together in the roller prior to being ultrasonically staked. The green and yellow rolls symbolise the + and – 30 degree orientations, and the red roll symbolises the 90 degree orientation. After the ultrasonic welding in the middle of figure 50 the continuous sheet is then cut to length using the travelling shear shown to the right hand side, after which the 5 ply sheets fall into a stack on a pallet.

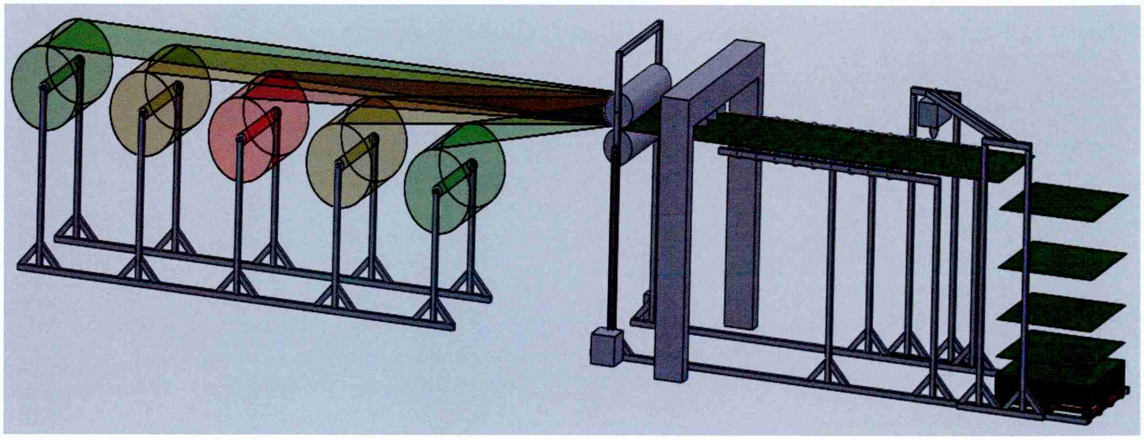


Figure 50: Stage 3 – Part Consolidation.

Stage 3 was validated by staking 5 layers of material together using an ultrasonic welder to form the part consolidated off axis laminate and checking they remained part consolidated.

5.1.4 Stage 4 – Full Consolidation:

After the 5 ply sheets have been cut to length they are heated to 190 degrees using infrared heaters prior to pressing into the final component. The sheets travel along a conveyor under the infrared heaters as shown in figure 51 before being presented into the press.

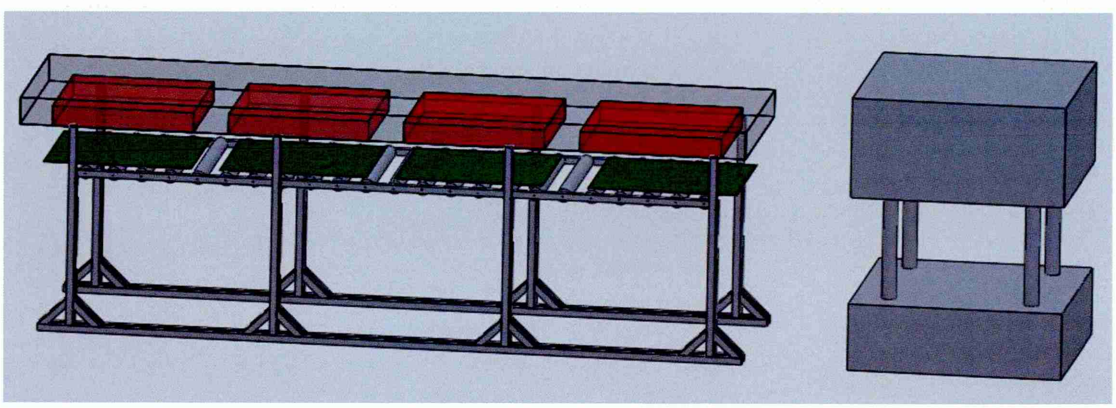


Figure 51: Stage 4 – Full Consolidation.

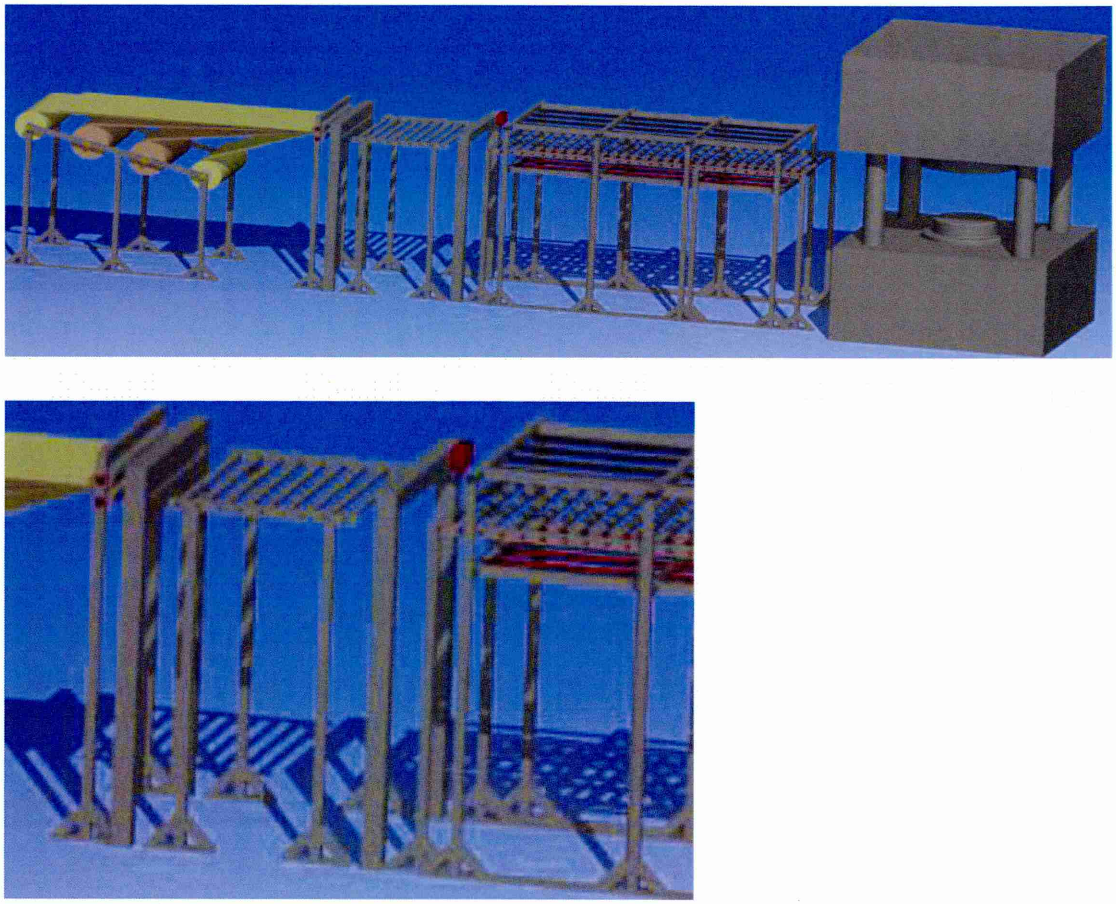


Figure 52: Stage 3 And Stage 4 – Iteration 2.

Stage 3 and 4 were further developed from their first iteration to become a single stage, stage 3. This stage still performed all the same functions as stages 3 and 4 did previously, however, performing them in a more streamlined manor with the part consolidated blanks from stage 3 travelling straight under the infrared heaters and into the press. The travelling shear has had the diagnal component removed to allow a single square cut to be performed when the material has been stopped for ultrasonic staking. This removes any errors that may occur by not cutting the material square due to varying speeds, if it was cut using a diagonal cutting path.

The estimated cost of manufacturing the machine as per concept 1, would be £224,000 in total with all three stages costing a similar amount as shown in table 12.

To validate stage 4 the author took the 5 ply part consolidated laminate stack up and passed it through some infrared heaters to determine if the material would soften sufficiently for full pressing which it did.

5.1.5 Estimated Cost of Producing Concept 1:

Table 12: Estimated Cost Of Concept 1

Estimated cost of concept 1			
Stage 1	2 hot air welding machines		£50,000
	control panel and motors		£10,000
	in house fabrications		£10,000
		Stage 1 total	£70,000
Stage 2	hot air welding machine		£25,000
	control panel and motors		£12,000
	bought out items (mandrel)		£5,000
	in house fabrications		£25,000
		Stage 2 total	£67,000
Stage 3	2 ultrasonic welders		£10,000
	traveling shear		£5,000
	in house fabrications		£15,000
	control panel and motors		£12,000
	Infrared heaters		£35,000
		Stage 3 total	£77,000
		Total cost	£224,000

5.1.6 Challenges With Concept 1:

The challenges that may be encountered if concept 1 was progressed would include;

- Matching the rotational speeds of the tube being formed, the compression roller, and the collection roller. The risk of the three items rotating with different angular velocities can be minimised by the control panel controlling the motors with feedback as any difference in speed could cause the tube to crack along the direction of the fibres.

- Another challenge that may be encountered is when heating the material under infrared. The infrared heaters are required to be extremely hot (600^{o}c) to ensure the central layer of material reached melting point at the processing speeds required. This causes the glass fibres in the outside layers to peel away from each other as the polypropylene tries to revert back to a sphere. This can be minimised by maintaining some form of surface contact on the surface of the material during the heating process.

5.1.7 Advantages of Concept 1:

The advantages of concept 1 include;

- An automated method of producing off axis fibre reinforced thermoplastic at mass production rates.

- A relatively simplistic production process – 3 processes.

- A modular production line allowing multiples of any stage to be used if required. This would become beneficial if the customer wanted more vehicle panels replacing in a vehicle.

- Off axis material to be collected and stored on a roll for use any time. This would allow the customer to gather a stockpile of off axis material for speedy production of components, or further resale should they so wish.

5.2 Concept 2 – Off Axis Sheet Method of Production:

Just like concept 1, concept 2 was broken down into manageable stages with a defined input and output required. These stages were then developed into an alternative method of producing the machine.

Concept 2 uses the same material widening process as concept 1, with stage 2 varying to produce a cut meter squared 2 ply material as opposed to a 2 ply off axis continuous roll. Stage 3 then uses the same input as stage 2, which is the output 1 meter wide roll of 90 degree continuous fibre reinforced material. Stage 3 cuts the roll of material into 1m lengths to produce a stack of meter squared sheets of 90 degree material. These are then combined with the output from stage 2 in stage 4 to produce a part consolidated material.

Stage 1 – Material widening.

Stage 2 – Tube forming.

Stage 3 – In line sheet production.

Stage 4 – Part consolidation.

5.2.1 Stage 2 – Tube forming:

The second stage of concept two still requires a mandrel with hot air welding equipment to form a continuous tube however concept two cuts the material using a travelling shear then compresses it to form a 2 ply off axis laminate layer as opposed to collecting the 2 ply laminate on a roll. The end product of stage 2 in concept 2 is a compressed 2 ply off axis meter squared of material. This is achieved by creating a continuous tube like in concept 1, then cutting it using a set of circular knifes which engage the material and cut at the same speed as the material is being produced. The travelling shear will cut the material every meter to produce a 1 meter tube with the fibres running at 30 degrees. The tube will then progress down the line via some internal rollers, where it will enter the compression rollers. These will grip the material at the entry point and drive it further into the compression roller unit squashing the tube as it progresses, until it passes the end drive rollers. These rollers are positioned with a gap twice the material thickness so the material is fully compressed thus snapping the glass fibres situated at the edge of the tube when it is passed through the end rollers.

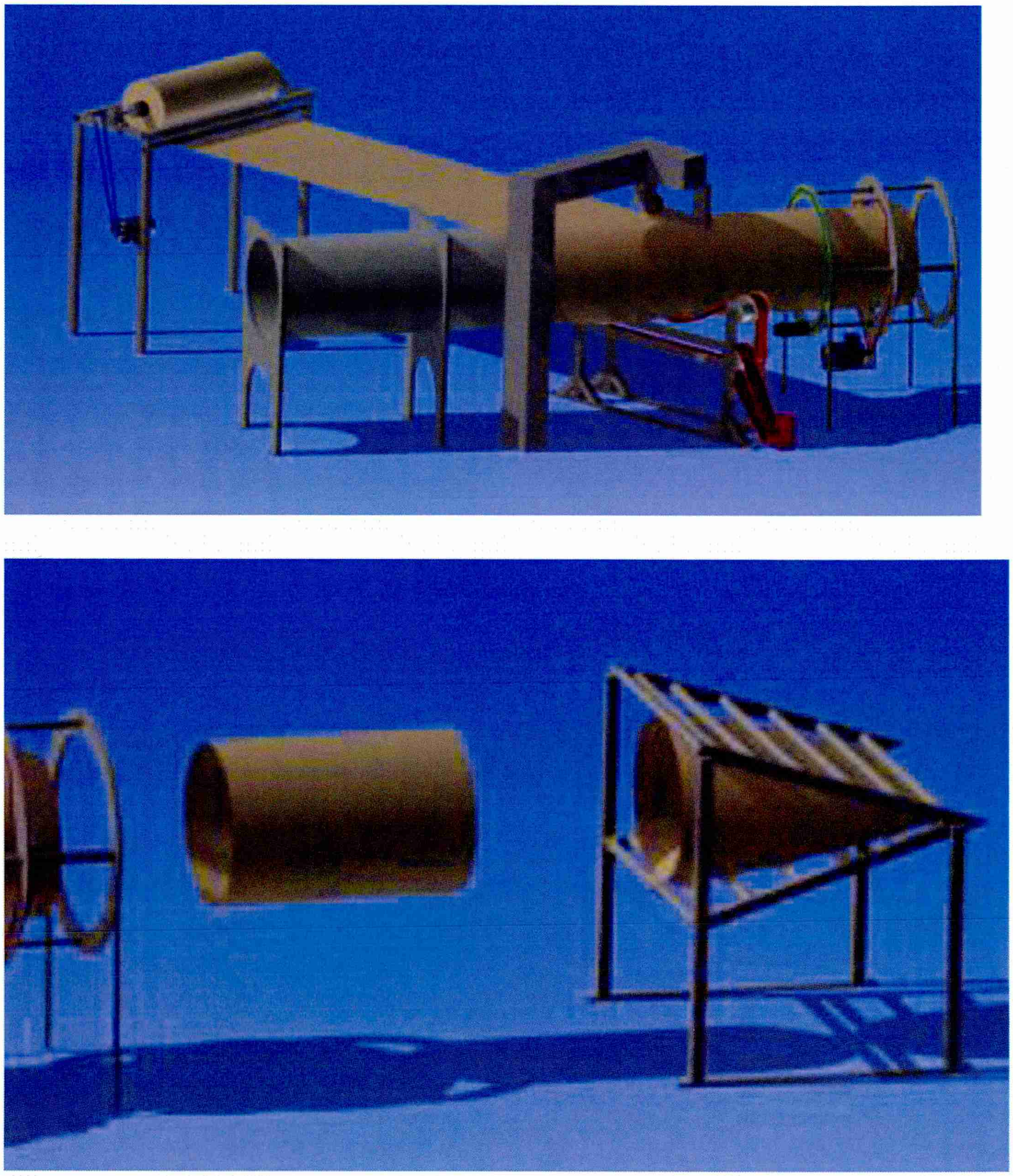


Figure 53: Concept 2 - Stage 2.

Stage 2 of concept 2 was validated in the same way as stage 2 in concept 1.

5.2.2 Stage 3 – In Line Sheet Production.

Using the continuous roll of material produced in stage 1, stage 3 cuts the continuous roll into meter lengths to be used along side the meter squared off axis material produced in stage 2. This is achieved by indexing the roll of 90 degree fibre reinforced material 1 meter, and actuating a guillotine powered by an air cylinder to cut the material. The cut lengths of material then travel down an angled table and are stacked on a pallet. Figure 54 below shows the roll of material traveling through the guillotine, then the cut lengths of material falling down the angled table into a pile to the right hand side.

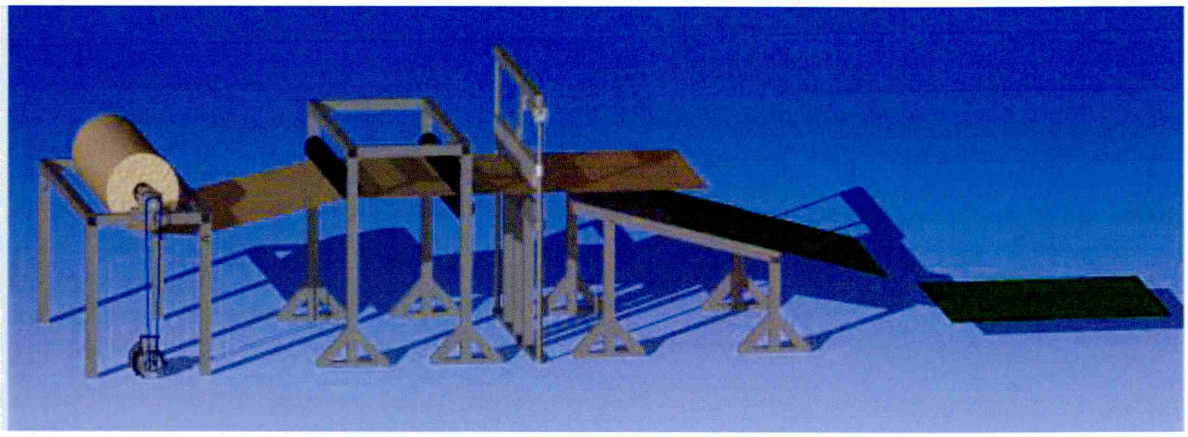


Figure 54: Stage 3 – In Line Sheet Production.

To validate stage 3 of concept 2 the author cut a widened sheet of unidirectional material into lengths using a guilotine which had been set up to shear the thermoplastic material.

5.2.3 Stage 4 – Part Consolidation.

Stage 4 brings together the sheets formed in stage 2 and 3, and stacks them in the required orientation to form the 5 ply off axis laminate with the orientation 90,30,-30,30,90. The laying up will be stacked by an operator who positions the layers of material in the correct orientation prior to ultrasonically staking them in 4 positions much like stage 3 of concept 1. Figure 55 below shows a table with ultrasonic welders mounted on a bridge so the material can be placed on the table in the correct orientation and staked together.

Figure 55: Stage 4 – Part Consolidation.

Stage 4 was validated using the same method to validate the ultrasonic staking of the material in stage 3 concept 1.

The estimated cost of manufacturing the machine as per concept 2, would be £192,000 in total with stage 1 and 2 costing the most at £70,000 and £75,000 with stage 3 and 4 costing only £25,000 and £22,000 respectively as shown in table 13.

5.2.4 Estimated Cost of Producing Concept 2:

Table 13: Estimated Cost Of Concept 2

Estimated cost of concept 2			
Stage 1	2 hot air welding machines		£50,000
	control panel and motors		£10,000
	in house fabrications		£10,000
		Stage 1 total	£70,000
Stage 2	hot air welding machine		£25,000
	control panel and motors		£15,000
	bought out items (mandrel)		£5,000
	in house fabrications		£30,000
		Stage 2 total	£75,000
Stage 3	guillotine		£10,000
	in house fabrications		£10,000
	control panel and motors		£5,000
		Stage 3 total	£25,000
Stage 4	Ultrasonic welders		£20,000
	in house fabrications		£2,000
		Stage 4 total	£22,000
		Total cost	£192,000

5.2.5 Challenges with concept 2:

The challenges that may be encountered if concept 2 is progressed would include;

- Cutting the tube into meter lengths using a travelling shear. The tube must be cut perpendicular to the direction of travel all the way around, or the meter long tube will be left with a slither of material which may snag and cause the tube to tear.
- Compressing the tube into a flat sheet of 2 ply off axis material. The output of this stage requires the tube to be flattened to 2 material thicknesses , thereby snapping the fibres at the edge of the material. The flattening of the tube will cause any crack or tear to continue throughout the length of the fibre, thus unravelling the tube.

5.2.6 Advantages of Concept 2:

The advantages of concept 2 include;

- An automated method of producing off axis fibre reinforced thermoplastic at mass production rates.
- A relatively simplistic production process – 4 processes.
- A modular production line allowing multiples of any stage to be used if required. This would become beneficial if the customer wanted more vehicle panels replacing in a vehicle.
- Production of off axis sheets can be palletised and stored for future use.
- Potentially endless length sheets can be produced with a width of 1m suitable for numerous applications.

Both concepts were presented to the board of directors at Joseph Rhodes detailing the estimated cost per concept, along with the advantages and challenges for each concept. After carefull consideration the board decided to go ahead with the manufacture of concept 2 with some minor modifications. These modificatoins included;

- Stage 4 would consist of 2 ultrasonic welding heads instead of 4. This was done to reduce machine cost as the ultrasonic weld takes 1-2 seconds. To achieve the 4 welds the material will be staked, rotated through 180 degrees then staked again. This change would reduce the machine cost by £10,000.

- The guillotine for stage 3 would be bought second hand and modified to make it automatic. This would greatly reduce the cost of stage 3 as a second hand guillotine could be sourced for approximatley £800, with £1000 of modifications. This would also reduce the strain in the drawing office.

Concept 2 was chosen as it produced off axis meter squared sheets of material which would be better suited to mass production applications and allow for additional revenue to be gained from the sale of sheets. The challenges highlighted in concept 1 detailing the rotating material collection unit presented major concerns with matching the speeds exactly which helped pursuade the board to consider concept 2. Another benefit of concept 2 was the end product of the machine would be a part consolidated laminate as opposed to a fully consolidated off axis laminate. This would allow the customer to produce a stock pile of part consolidated laminates which could be either stored or sold, without the need to melt them into a fully consolidated laminate. This would reduce the energy required to produce a component as it only needs melting immediately prior to pressing. If the machine produced fully consolidated laminates they would have to be remelted prior to pressng. The added advantage of the machine being produced in stages allows the customer to purchase multiples of each portion of the machine should they wish to relieve a bottle neck in production for example 2 x stage 1 to simultaneously produce off axis and in line fibre reinforced sheets.

Chapter 6 – Refined Machine Design.

6.1 Introduction

The design process began by identifying which bought out parts would be required for each stage and determining what needed to be designed to interact with those to ensure the achievement of the design functioned as expected. The bought out parts required per stage were;

Stage 1 – Double hot air welding machine (Pfaff 901-4506-002/001) running at 600˚C and up to 40 m/min linear welding speed with an air exhaust volume of 150L/min which joins the 3 rolls of raw material into a single roll.

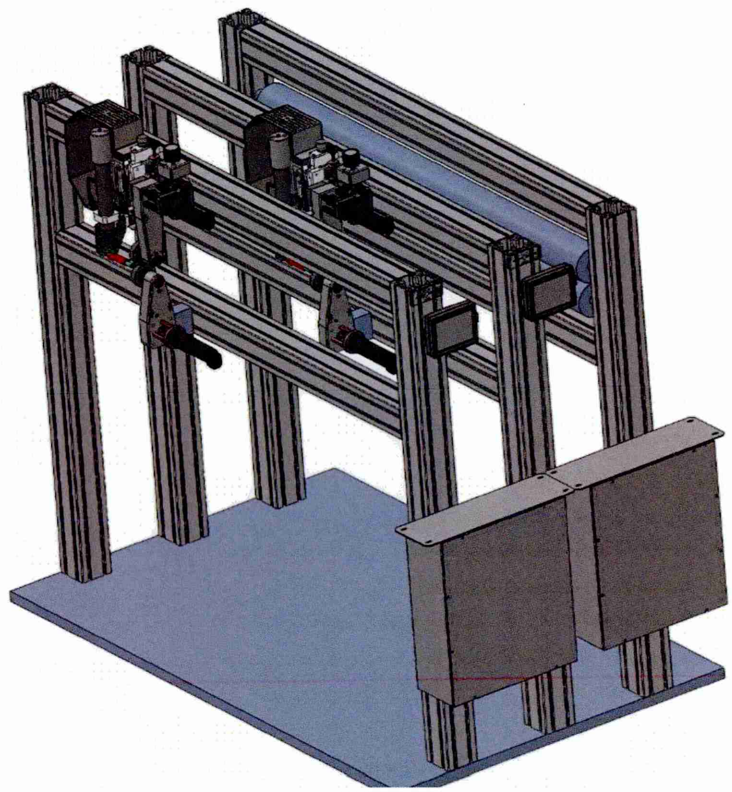


Figure 56: Cad Model Of Pfaff Double Hot Air Welding Machine

Figure 57: Hot-Air Or Hot-Wedge Sealing Equipment For Programmed Sealing (Pfaff Industrial 2013).

Stage 2 – Single hot air welding machine (Pfaff 901-4506-001/001) which welds the material from stage 1 into a continuous tube around the mandrel.

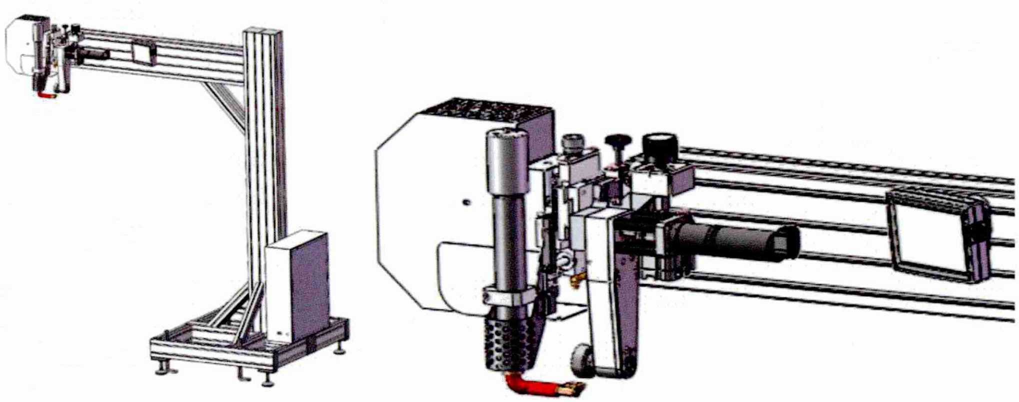


Figure 58: Cad Model Of Pfaff Single Hot Air Welding Machine.

Stage 3 – Guillotine which cuts the unidirectional material into meter sheets.

Stage 4 – Ultrasonic welding machine/s (Southfork Innovation 35/800) which stake the multiple layers of material into a part consolidated sheet.

Comprising :

35KHz 800w generator M version housed within a case.

Pneumatic actuator VE35 / 32-40 [32mm diameter – 40mm stroke]

3.5m coaxial cable for the HT supply to converter.

3.5m control cable.

Converter type DN35/1200 rigid.

Hardened steel sonotrode with profile as per trials.

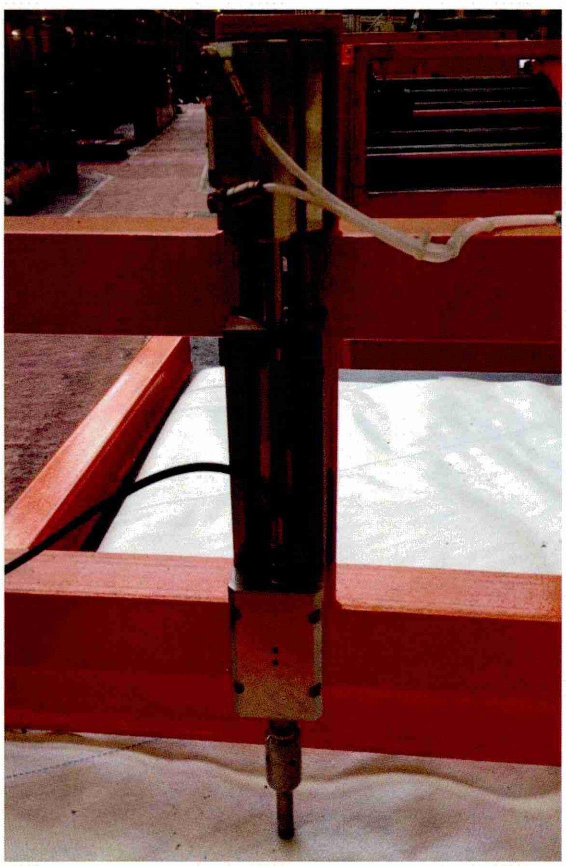


Figure 59: Ultrasonic Welding Unit

6.2 Stage 1- Material Widening.

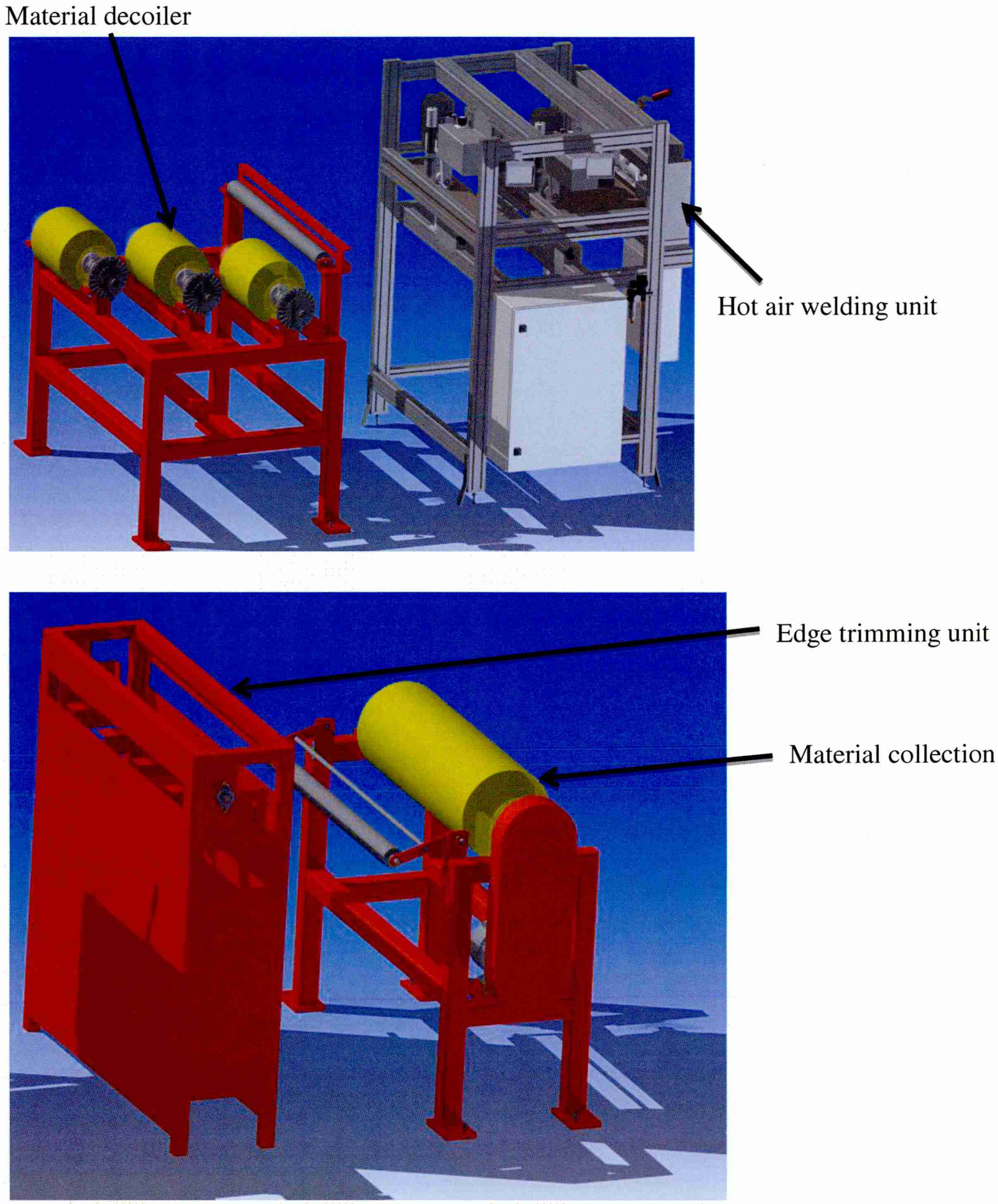


Figure 60: Concept 2 – Stage 1 Decoiler & Hot Ait Welding Unit (top), Edge Trimming Unit & Material Rewind (bottom)

The function of stage 1 involves 3 rolls of raw material 343mm wide being joined with a hot air weld, trimmed to an exact width then collected on a reel ready for processing on stage 2 and 3 as shown in figure 60 above.

The roll which is presented to stage 2 (required output of stage 1) must be an exact width to allow a suitable weld to be achieved on the mandrel. This will be ensured by setting the edge trimming blades 1010mm apart so the width of material presented to the mandrel is 1010mm wide allowing for a 10mm helical weld to be achieved on the mandrel. This allows a weld of 9.5mm to be used to join the raw material rolls into a 1 meter wide roll.

The assembly of stage 1 consists of 4 sub-assemblies which are controlled by a control panel. Going from left to right these subassemblies are;

1) Material decoiler
2) Double hot air welding equipment
3) Edge trimming unit
4) Material collection roller.

Double hot air welding equipment:

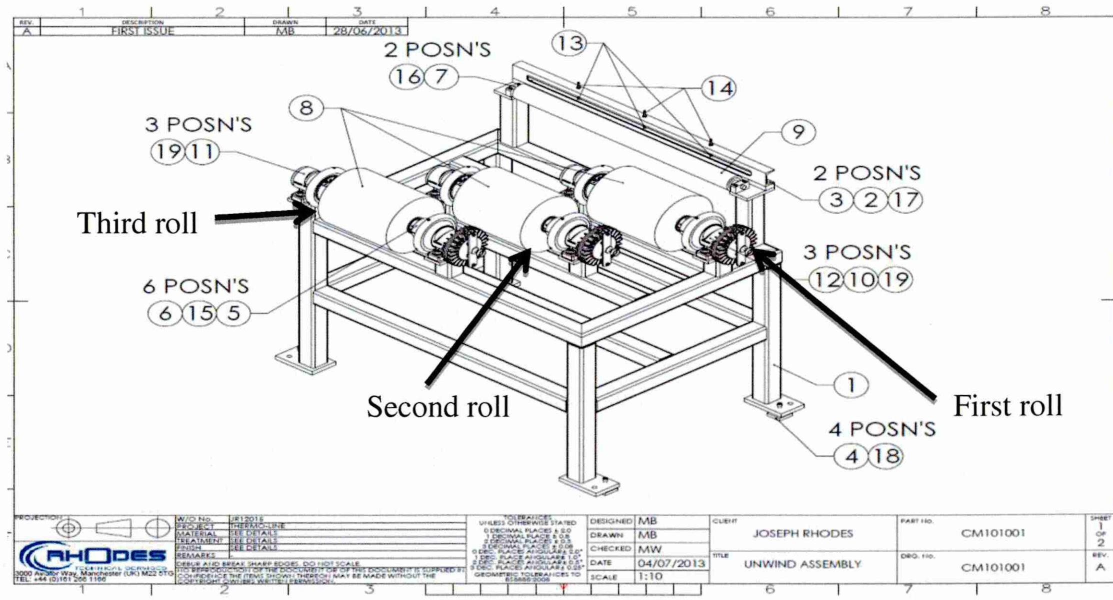
The double hot air welding unit is the most important part of stage 1 as it joins the raw material together and produces material as wide as the project requires. The hot air welding machine required to perform the weld to join the rolls of material was purchased from a company called Pfaff (http://www.pfaff-industrial.com/pfaff/en/pfaffstart) who conducted the trials on the material for us. They overlapped the material approximately 10mm and passed it through 2 nip rollers which had a hot air nozzle directed in between the layers exhausting air at a rate of 150L/min, and temperatures of 600^{o}c. in doing this they performed a hot air weld at speeds up to 40m/min. Following several meetings with the Pfaff representative in which the author detailed the desired running height, presentation of material into the machine and machine controls Pfaff built a bespoke double hot air welding machine for our application. The machine had to achieve a suitable weld at 40m/min and needed to have a running height of 1200mm which was level with the height of the material unwind and the edge trimming unit. The hot air welder also needed to be controlled by a remote control panel which would control every function of stage 1.

Material decoiler:

Following the design of the hot air welding machine, the next most important part of stage 1 is how the material is presented to the hot air welding equipment. The 3 rolls of material entering the hot air welding machine had to be level, with the desired overlap already present, for example a 9.5mm overlap between the first and second roll, and a 9.5mm overlap between the second and third roll as shown in figure 61.

To achieve the overlap required by the three rolls of material they needed to be positioned on a fabricated frame with each roll on a separate shaft to allow each roll to be positioned overlapping 9.5mm into the next roll.

This was achieved by designing a frame with 3 offset shafts which positioned the rolls with the appropriate overlap, and a tensioning roller positioned at the running height of the hot air welder. Figure 61 below shows a portion of the detailed drawing of the fabricated frame for the material unwind station showing the 3 offset shafts. The first roll of material would be positioned on the front shaft to the right hand side so that when the second roll of material is positioned on the middle shaft when it is unravelled it goes over the first roll and overlaps by 9.5mm. The third roll will then be positioned on the rear shaft so that when it is unravelled it overlaps the middle roll of material by 9.5mm also. Due to the raw material being pulled through stage 1 by the hot air welder and the material collection roller at the end of stage 1, the material decoiler does not need to be motorised. To apply some tension to the material as it is being pulled through the stage and to ensure the rolls do not unravel, each shaft needs a brake to apply minimal pressure to the roll to stop it from unravelling. Manual bakes were used for this as the amount of pressure will vary as time progresses with the diameter of the roll decreasing, and the rotational speed of the roll needing to increase to maintain the same linear speed of 40m/min.



ITEM NO.	PART NUMBER	DESCRIPTION	SUPPLIER	MATERIAL	QTY.	REMARKS
19	SHCS M12 x 50	SOCKET HEAD CAP SCREW			12	-
18	SHCS M12 x 45	SOCKET HEAD CAP SCREW			4	-
17	SHCS M8 x 50	SOCKET HEAD CAP SCREW			4	-
16	SHCS M8 x 45	SOCKET HEAD CAP SCREW			4	-
15	SHCS M6 x 30	SOCKET HEAD CAP SCREW			12	-
14	BOS 08M-PS-RE11-S49	THROUGH BEAM SENSOR	BALLUFF		3	B/O
13	BOS 08M-X-RS11-S49	THROUGH BEAM SENSOR	BALLUF		3	B/O
12	30-40 STW	SAFETY CHUCK [SHAFT]	RIMOR		3	B/O
11	30-40 STO	SAFETY CHUCK [PLAIN]	RIMOR		3	B/O
10	30-40 ESB	MECHANICAL BRAKE	RIMOR		3	B/O
9	STEEL ROLLER	STEEL ROLLER	AED ROLLERS		1	B/O
8	REINFORCED COMPOSITE ROLL [25Kg]	PRODUCT	JOSEPH RHODES		3	B/O
7	CM100007	BEARING BLOCK		ALUMINIUM 6082	2	-
6	CM100005	UNWIND SAFETY CHUCK BAR		EN24	3	-
5	CM100004	ROLL CLAMP		M/S	6	-
4	CM100003	JACKING PAD		M/S	4	-
3	CM100002	SENSOR STRIP		M/S	1	-
2	CM100001	SPACER BLOCK		M/S	2	-
1	CM100000	UNWIND FAB		M/S	1	-

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Figure 61: Material Decoiler Fabrication Drawing & Parts List.

Edge trimming unit:

After the running heights had been set by the hot air welding equipment and the material decoiler, the edge trimming unit could be designed. The edge trimming unit has a very simple function i.e. to trim the material to a desired width ready for collection into a single roll. This was designed with two circular cutters screwed into a motorised shaft with two lengths of angle iron acting as the other cutting face. The lengths of angle iron had a machined face which acted as a cutting face. Both cutting blade and angle iron were movable along the length of the edge trimming unit to allow varying widths of material to be achieved. The cutting blades must run at the same speed or faster than the material which it is cutting to avoid the material snagging and tearing. The blades were designed with a diameter of 100mm, so to achieve a linear speed of 40m/min or greater the blades had to rotate at a rate of 127.3RPM or greater. The selected motor and gear ratio provided a rotational speed of 500RPM for the blades which was more than sufficient.

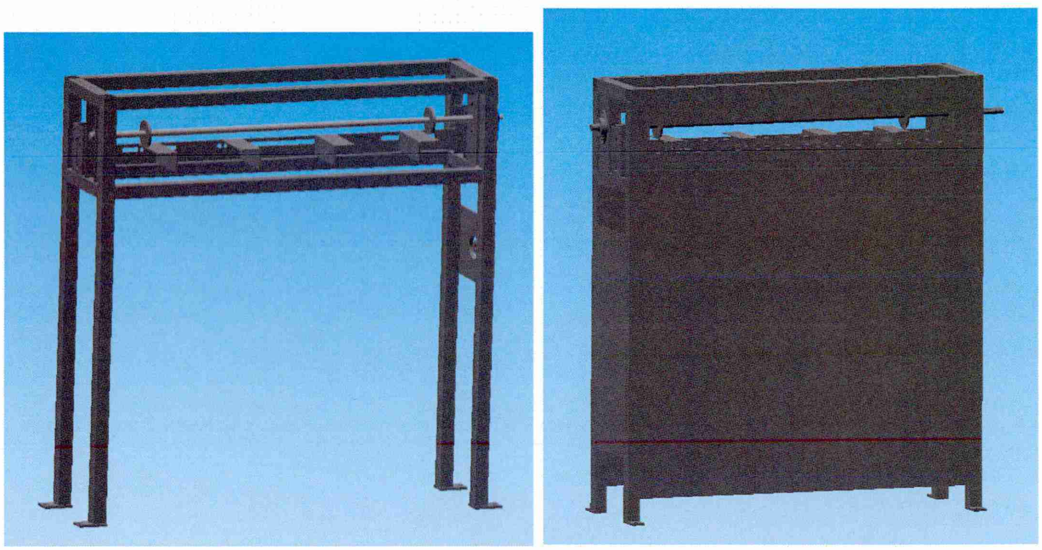


Figure 62: Edge Trimming Unit

Material collection roller:

The last thing to be designed in stage 1 is the material collection roller. The material collection roller is positioned after the edge trimming unit and collects the material at a decreasing rate as the collection roller increases in diameter. The variable speed of the material collection roller is controlled using a potentiometer positioned at the pivot of a dancing arm. The potentiometer rotates through a percentage of a turn depending on if the dancing arm is raised or lowered. The position of the dancing arm is set so it applies tension to the material so it can be wound tightly on the roll. If the arm is raised from this set position, the collection roller is rotating too quickly, so the potentiometer tells the control panel to reduce the speed of the motor, likewise if the arm drops from this position the potentiometer tells the control panel to speed the motor up.

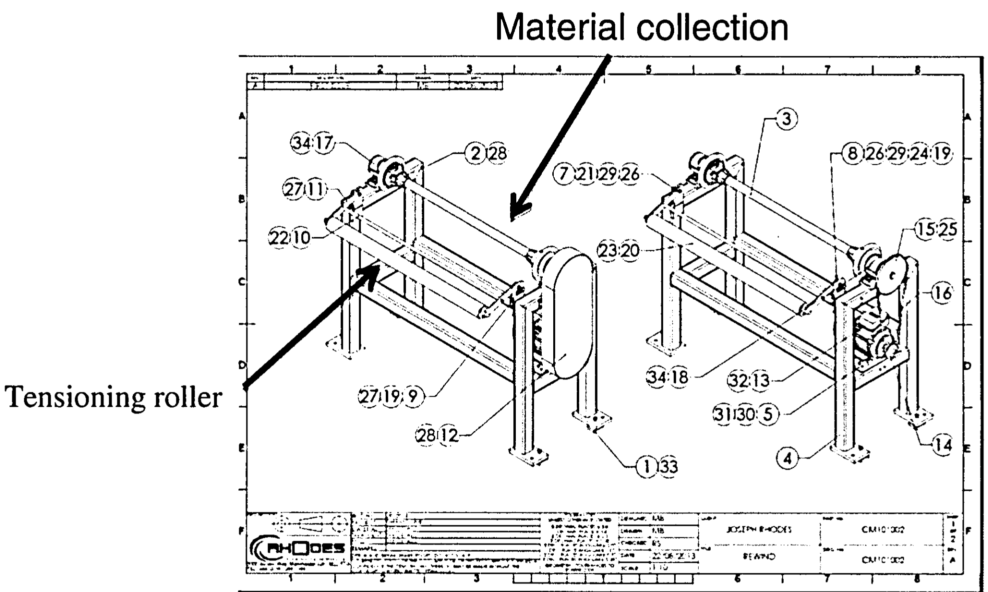


Figure 63: Material Collection Assembly.

Control panel:

Stage 1 is then controlled by a control panel which allows the speed and temperature of the hot air welding equipment to be manually adjusted, as well as the speed of the edge trimming unit, while the speed of the collection roller is governed by the potentiometer on the dancing arm. The programming and design of the control panel was sub contracted to a company called HMK following a meeting to discuss the function of the machine, requirements of stage 1, and which parameters needed to be controlled.

Figure 64: Control Panel For Stage 1

6.3 Stage 2- Tube forming.

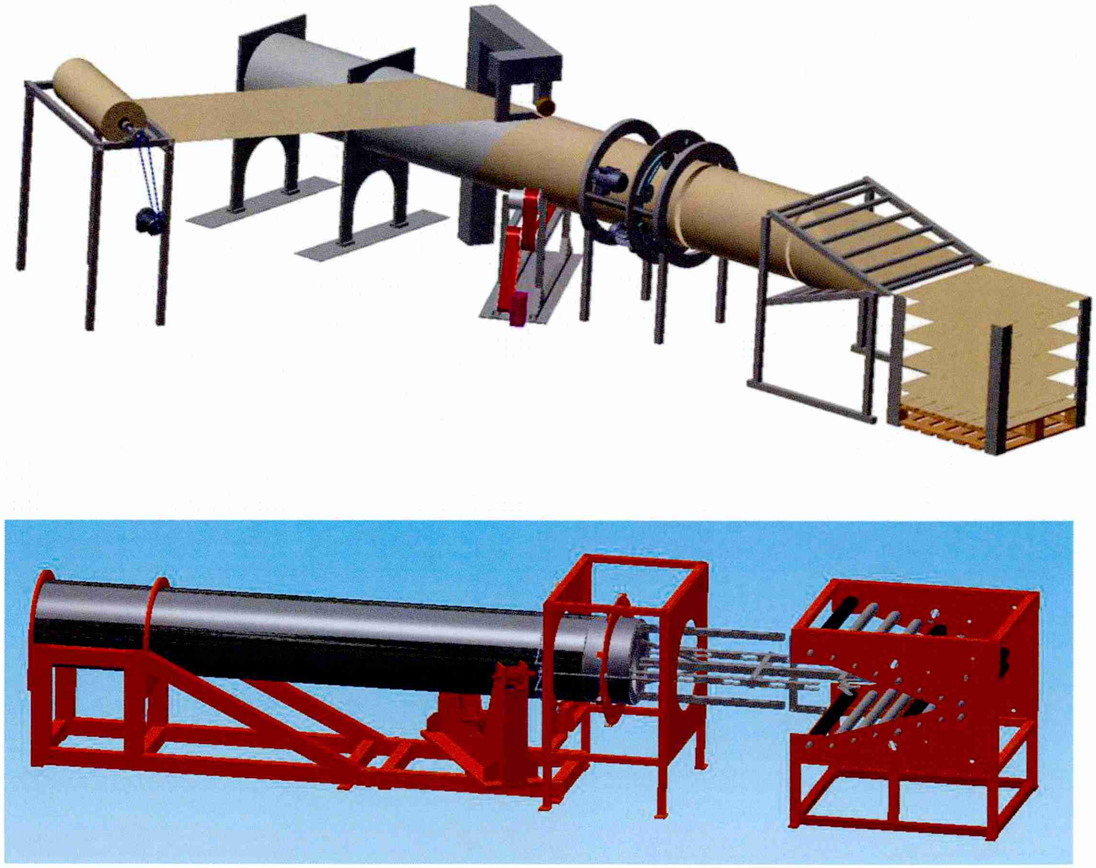


Figure 65: Stage 2

Stage 2 receives the rolls of material produced in stage 1, and welds them into a continuous tube using a single welding head. The material entry angle, is critical to the function of stage 2 because if the angle of entry is out by a degree or two the overlap for the weld will either increase or decrease (depending on which way the angle is out), and it will either become too tight to wrap around the mandrel, or too slack and not produce a tube. Once a continuous tube has been formed a travelling shear matches the speed of the tube after 1m of tube has passed the cutter and performs a circumferential cut to produce 1m of off axis fibre reinforced tube. This tube is then gripped by the front rollers of the compression roller system and flattened into a meter squared sheet of 2 ply off axis material which is collected on a pallet ready for processing on stage 4.

The design of stage 2 was broken down into 5 parts, the mandrel, the hot air welding equipment, the material decoiler, the travelling shear and the compression rollers.

The most important part of stage 2 is the mandrel and mounting the hot air welding equipment to ensure the tube can be formed using a continuous weld. To achieve this, a mandrel of 636.6mm outside diameter was made from a steel tube with a bracket welded onto the inside of the tube to mount the lower arm of the hot air welding equipment. The mandrel then needed to have a slot cut into it for the bottom roller of the hot air welding machine to protrude through, to perform the joining weld, as well as having means for support rollers to carry the material after it had been cut, and carry it to the compression rollers. The mandrel was designed to accommodate the bottom roller of the welding equipment by bolting it to the mandrels internal bracket ensuring the bottom roller protruded through the outside diameter of the mandrel by 2mm. This would create a tube which was 2006mm in circumference to ensure the tube did not become tight on the mandrel. It then had a shorter tube bolted onto the end of the mandrel with the same diameter as the mandrel for the cutting blades to cut the continuous tube to meter lengths. A section of 4 arms with rollers attached then bolted onto the end of the cutting section of the mandrel to support the tube as it was progressing. The rollers supported the tube and maintained its circular structure prior to it entering the compression rollers.

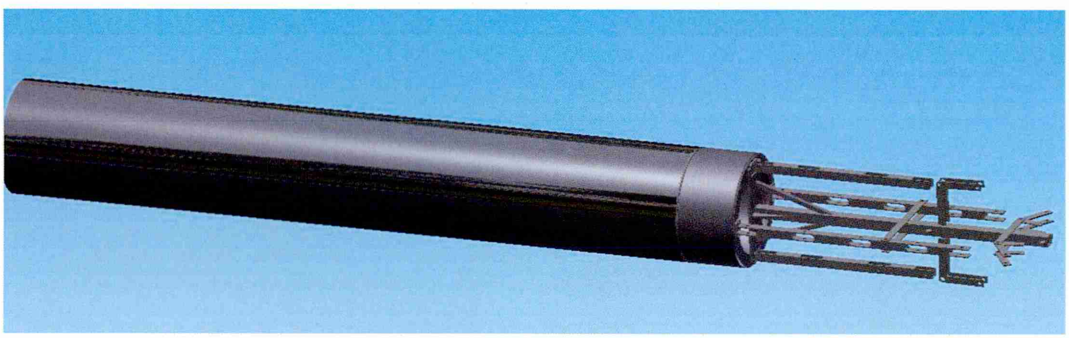


Figure 66: Mandel With Support Roller Frame

A frame was designed for the mandrel so it would be supported at one end, allowing the thermoplastic tube to continue as is was being created. The frame needed to hold the mandrel while the thermoplastic material was wrapped around it at 30 degrees and welded ensuring the material did not come into contact with the frame. A frame as shown below was designed to hold the mandrel in position at one end, and allow the material to wrap around the mandrel at 30 degrees without contacting the frame. The frame also incorporated a rubber backed belt drive to drive the thermoplastic around the mandrel as the tube was being produced. The linear speed of the belt had to match the linear speed of the weld, otherwise the tube would tear apart as it progressed down the mandrel.

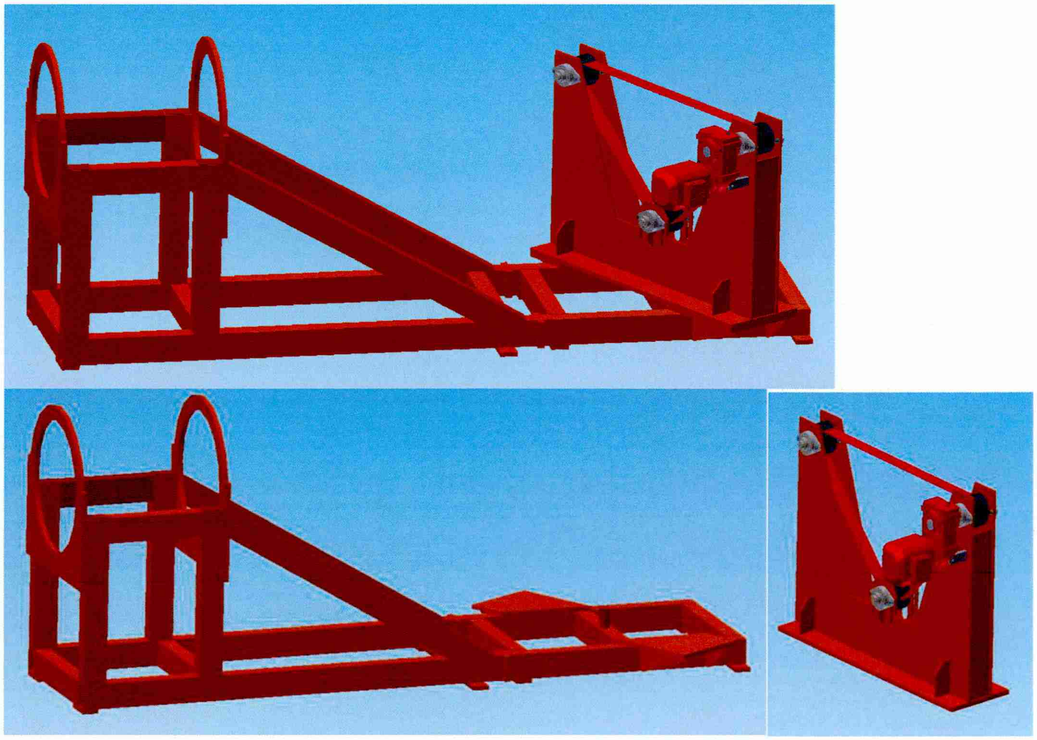


Figure 67: Mandrel Support Frame With Incorporated Belt Drive.

The hot air welding machine had to weld at the same linear speed as those used in stage one, as well as ensuring the frame of the welding equipment could be positioned around the frame of the mandrel and have a set operating height which was in line with the running height of stage 2. This was all discussed with Pfaff prior to them designing the hot air welding machine for our application.

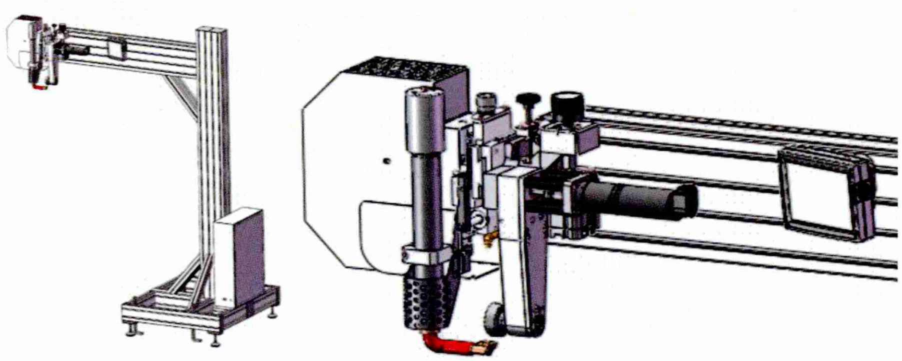


Figure 68: Cad Model Of Pfaff Single Hot Air Welding Machine.

Once a continuous tube had been produced, it was cut into lengths of 1m using a travelling shear. This was designed with 8 circular cutting blades positioned equally around the periphery of the tube, mounted to a ring which travelled on a lead screw. The lead screw would speed up to match the speed of the tube, engage the cutters, perform the cut while the tube rotated through 50 degrees, (so each cutting blade cut beyond the position of the previous cutting blade), disengage the cutters, slow down and return to the start position ready to cut the next tube. The cutting blades were attached to an air cylinder each which actuated and fired into place to perform the cut when required.

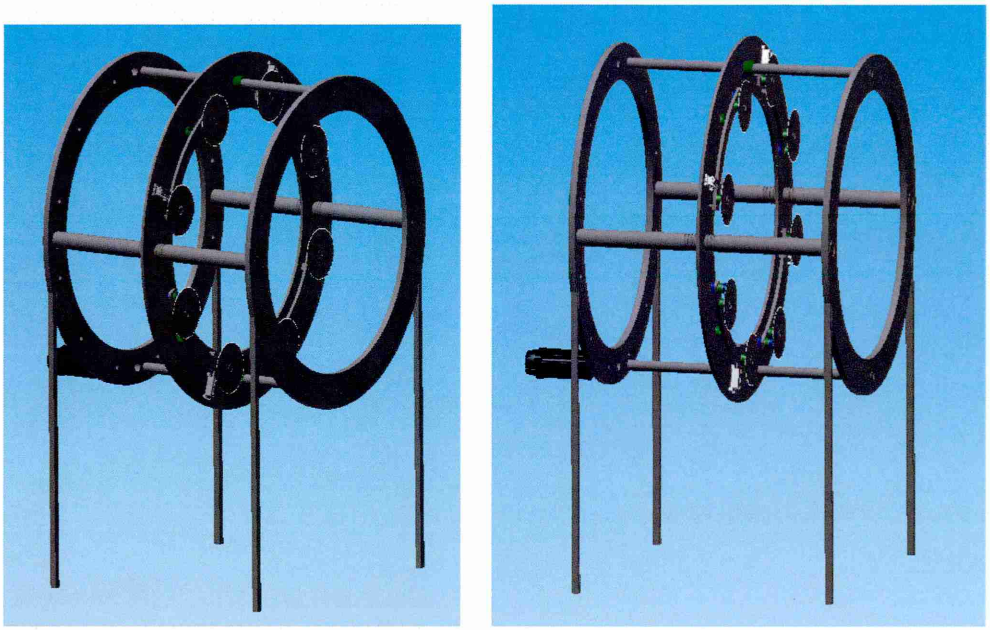


Figure 69: Travelling Shear.

With the tube now cut into a length of 1 meter, it would be pushed along the rollers by the next tube until it engaged with the first roller of the compression roller assembly. This section of stage 2 compresses the cut length of tube to a flat 2 ply sheet of off axis material. It uses a set of rollers positioned in a V shape to compress the tube until it is flattened on the centreline of the mandrel.

The speed of the compression rollers is 5% faster than the production speed of the tube so it is taken away from the end of the mandrel as soon as it engages with the rollers, allowing minimal effort in pushing the tube as the continuous tube progresses.

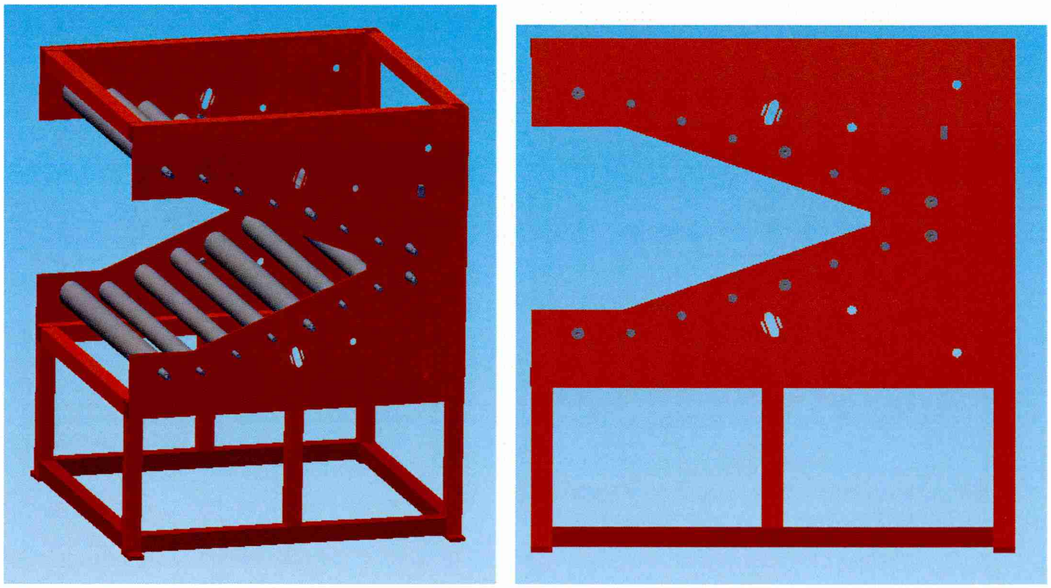


Figure 70: Compression Rollers

A material decoiler was designed to take the finished roll of material from stage 1 and allow it to be wrapped around the mandrel prior to being welded into a continuous tube. This material decoiler had to have a manual brake just like those used on the material unwind portion of stage one, and maintain a constant running height as the diameter of the roll decreased.

Figure 71: Material Decoiler

6.4 Stage 3 – In Line Sheet Production:

Figure 72: Stage 3 – Inline Sheet Production

Stage 3 receives the widened roll of material produced in stage 1, indexes it by 1 meter and cuts it to length using a guillotine producing a stack of in line fibre reinforced sheets 1 meter long. These sheets are then stacked on a pallet and will be used in the laminate stack up as the 90 degree orientation sheets.

The guillotine was purchased as a second hand item to cut down design time and costs. The guillotine was capable of cutting material up to 1200mm wide, and shearing steel up to 3mm thick. This was then modified to have two pneumatic cylinders mounted to the underneath so the cutting could be automated as well as having the blades sharpened and it set up to cut the thermoplastic material.

A table was fabricated at an angle to take the material after it had been cut and stack it onto a pallet positioned at the bottom of the table.

Figure 73: Guillotine Table.

Next I designed a set of nip rollers which would take the material from the roll and index it a given length (in this case 1 meter). The nip rollers were controlled by the machines PLC, so it could index any length should the customer wish to make longer components.

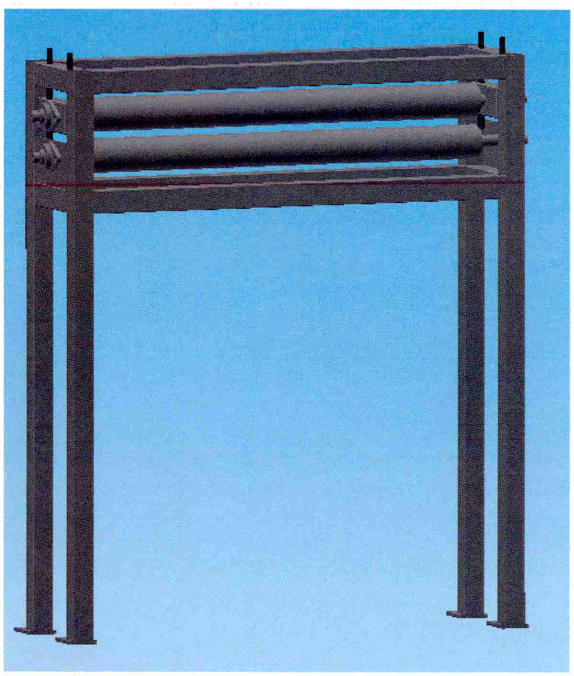


Figure 74: Stage 4 Nip Rollers

The material decoiler for stage 2 was duplicated so it could be used in stage 3 as it performed the same operation as was required for stage 2.

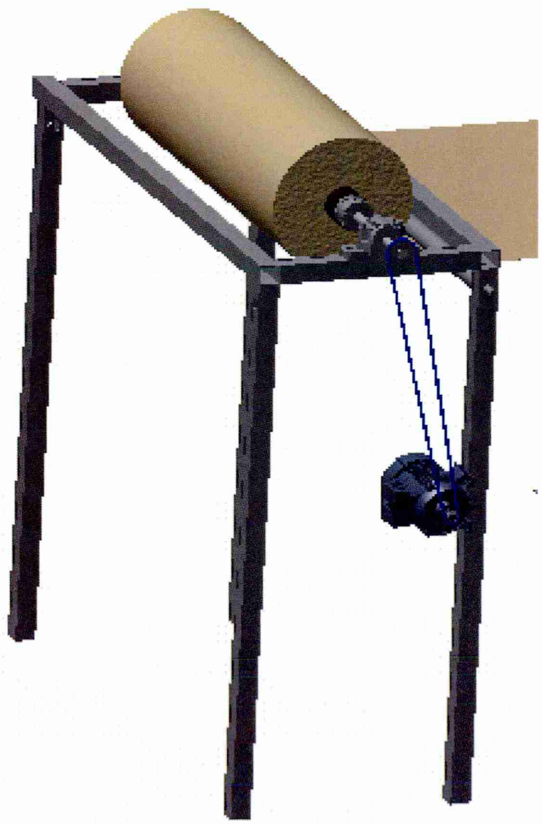


Figure 75: Material Decoiler

6.5 Stage 4 – Part Consolidation:

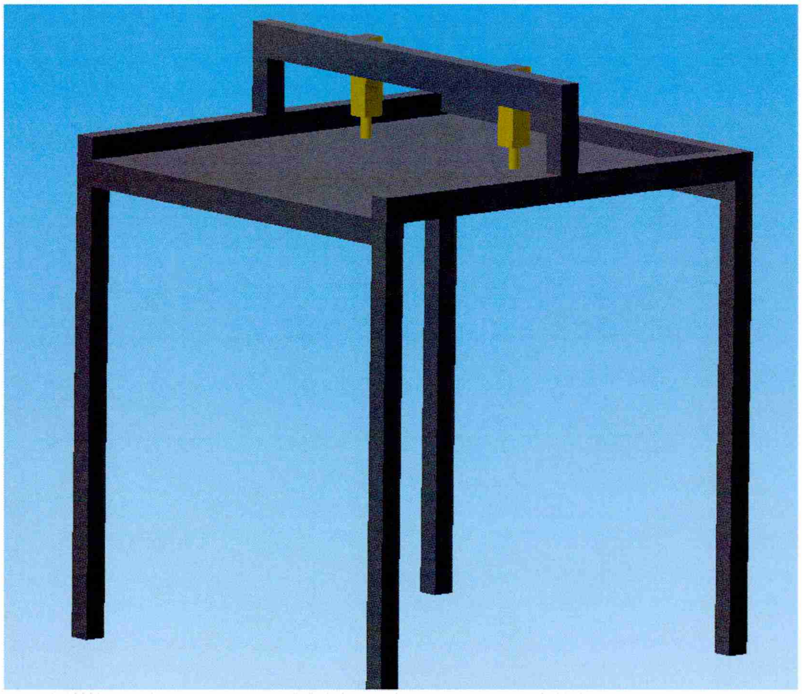


Figure 76: Stage 4 – Part Consolidation

Stage 4 utilises the meter lengths of material produced in stage 2 and 3, and stacks them up into the orientation determined in chapter 3 (30,-30,90,-30,30) this would require 2 of the 2 ply sheets produced in stage 2 and 1 of the in line sheets produced in stage 3. Once they have been stacked up they are staked into position using 2 ultrasonic welders before being turned around and staked again. This produces 4 equally spaced ultrasonic stakes to keep the laminate stack up together prior to heating and forming. It was decided to reduce the number of ultrasonic welders from 4 to 2 to save costs as the welding process takes 1.5-2 seconds.

The sheets of material from stage 2 and 3 are presented to an operator on stage 4 in the form of pallets. The operator then stacks up the laminate on a fabricated table ensuring it is in the correct orientation and performs the weld. The ultrasonic welders are secured in position above the laminate by a bridge which is fabricated to the table. The ultrasonic welders themselves are a bought out component from South Fork Innovation who performed trials on the material and specified that a welder with a 35mm diameter knurled horn operating at 35KHz would be able to perform a sufficient weld to keep the laminate together.

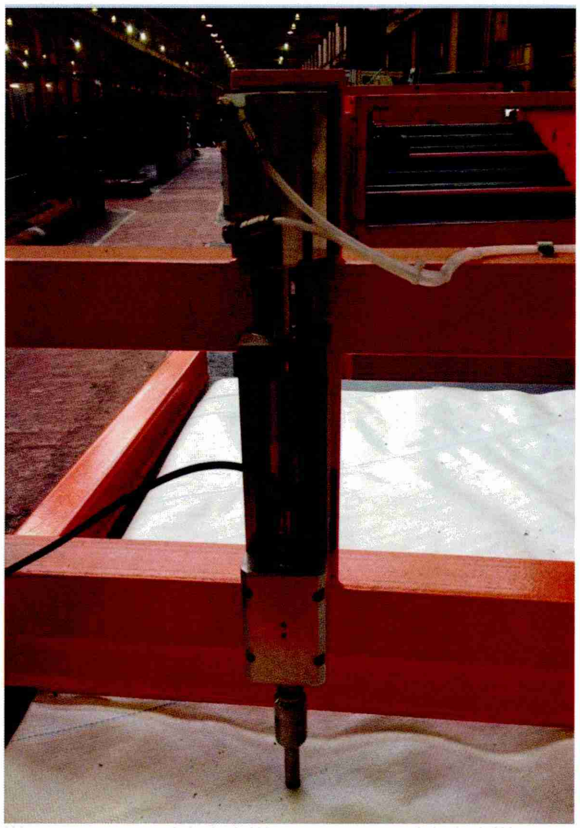


Figure 77: Ultrasonic Welding Unit

Chapter 7 – Sample Component Production:

7.1 Pressing of Top Hat Section:

The author contacted the University of Warwick to enter into discussions involving the use of their composite pressing facility. Following the discussions Warwick University allowed the author to use their heating platens, top hat mould, and press to form a top hat section from the laminate stack up derived in section 3.

The author created a part consolidated off axis laminate, which was then fully consolidated by heating it in between two heating platens with a layer of PTFE on the top and bottom of the laminate to provide surface contact as shown in figure 78.

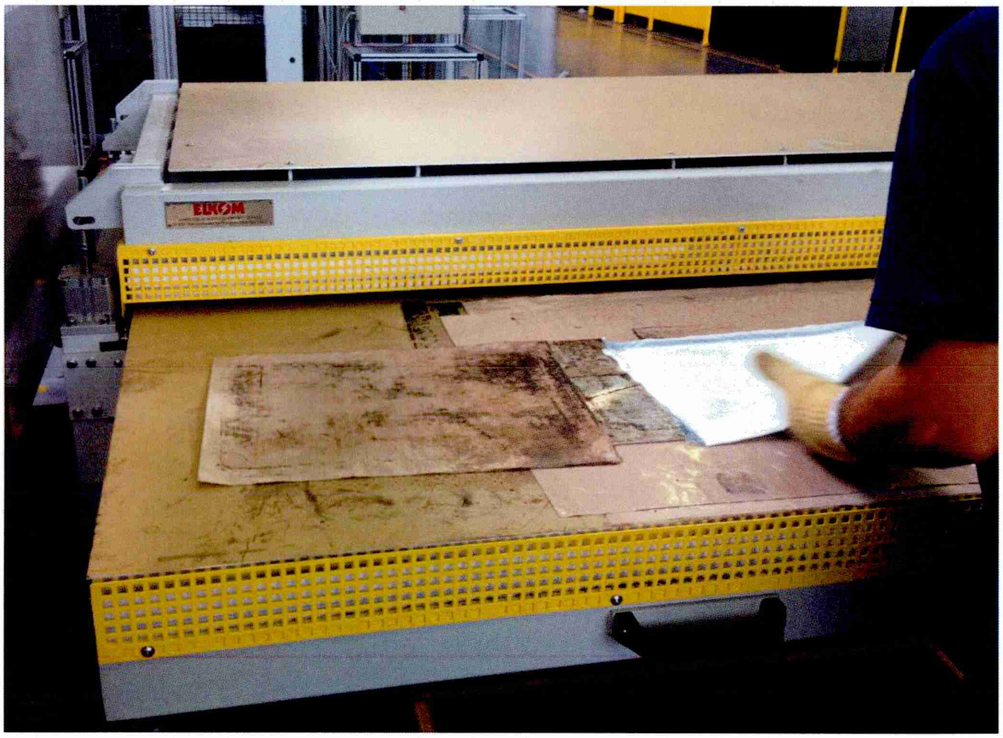


Figure 78: Thermoplastic Sample Heating On Elkom Heater.
[http://www.elkom.de/en/produkte/composites/electrically-heated-platens.html]

The surface contact was provided so as the material reached melting point the matrix would spread throughout the surface of the PTFE film and allow the heat to propagate throughout the laminate through contact until it was all softened. Figures 79 an 80 show the part consolidated laminate being heated under the heating platens (figure 78) using PTFE for surface contact. These figures show the laminate softening throughout without any signs of cracking or fibre separation.

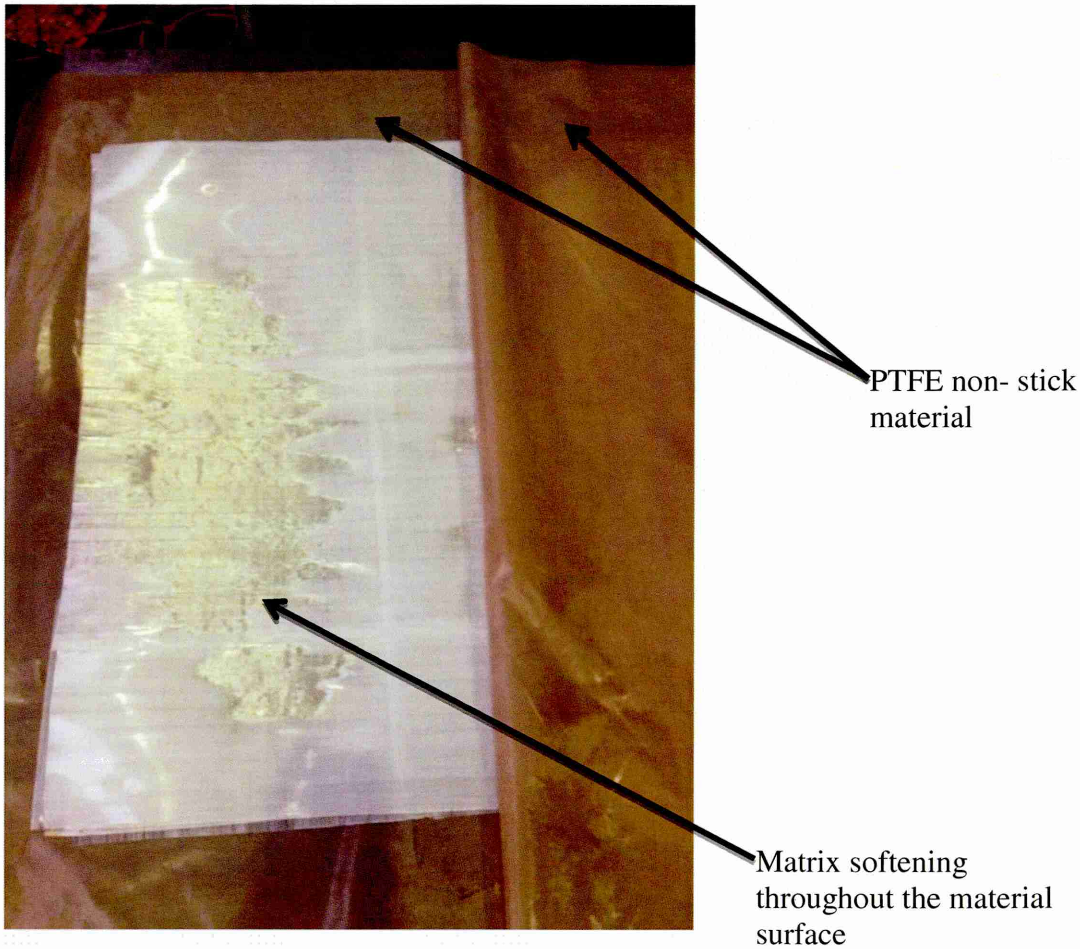


Figure 79: Thermoplastic Heating With Surface Contact

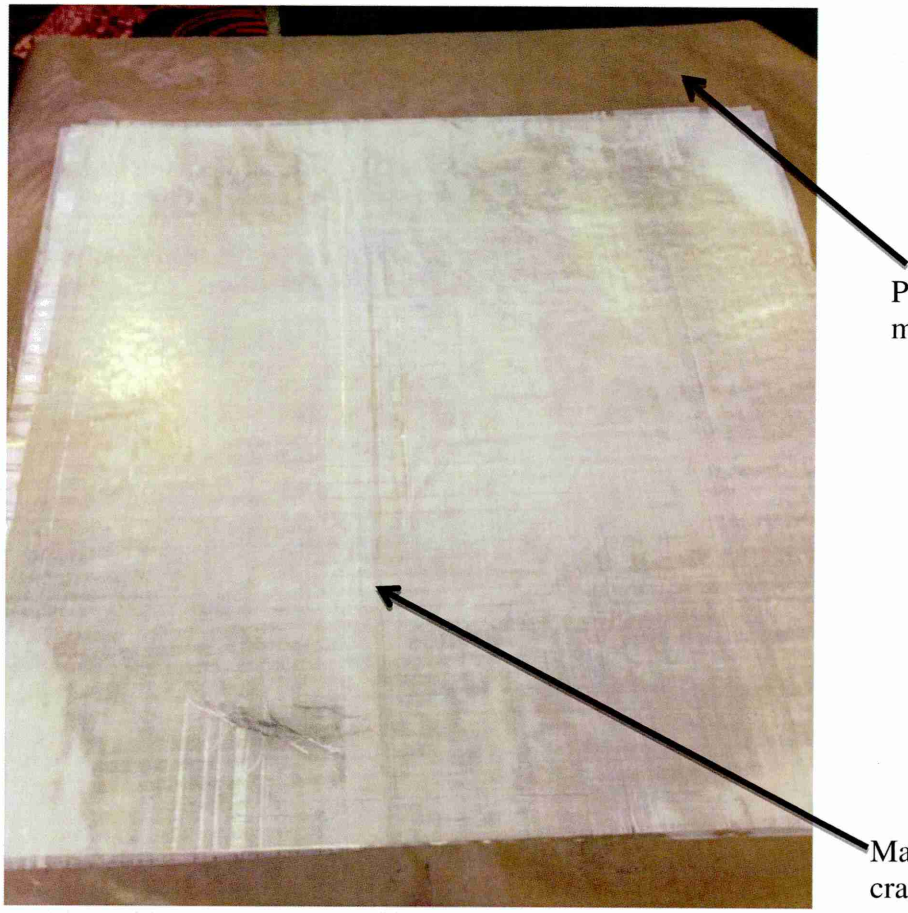


Figure 80: Fully Softened Laminate With Surface Contact.

Without surface contact the matrix in the part consolidated laminate would bead along the fibre length causing fibre separation within the laminate layers and an effect which resembles cracking. Figure 81 shows a part consolidated laminate layer heated in an oven with no surface contact to allow the matrix to flow along the surface of the laminate. This has resulted in the top layer of the laminate heating up and warping before the lower layers of the laminate have started to soften. As the top layer of the laminate heats faster than the rest of the laminate, and begins to soften, with out surface contact the matrix begins to flow along the length of the fibre allowing the fibres to separate from each other and give the effect of the laminate cracking. Once this has occurred the position and alignment of the fibres has changed from being in line with the rest of the laminate layer and cannot be corrected to be inline.

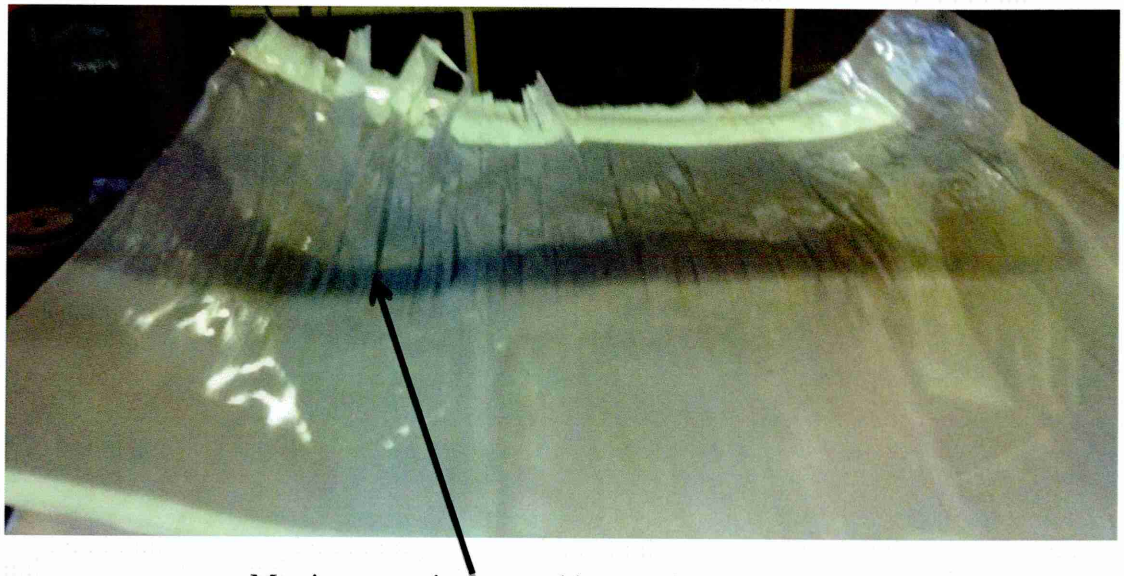


Figure 81: Thermoplastic Heating With No Surface Contact.

To create a fully consolidated laminate the part consolidated laminate was heated to 190^{o}c in the Elkom heater shown in figure 78 and held at that temperature for 5 minutes. The softened laminate was then transferred to the press where it was pressed into either a flat sheet or a top hat section.

The flat fully consolidated sheet of material was examined through a light source to distinguish the fibre direction within the sheet. Figure 82 shows a 5 ply fully consolidated laminate with fibre direction. As figure 82 shows, there are fibres in the vertical direction (90 degrees), and two lots of off axis fibres (at 30 degrees, and -30 degrees)

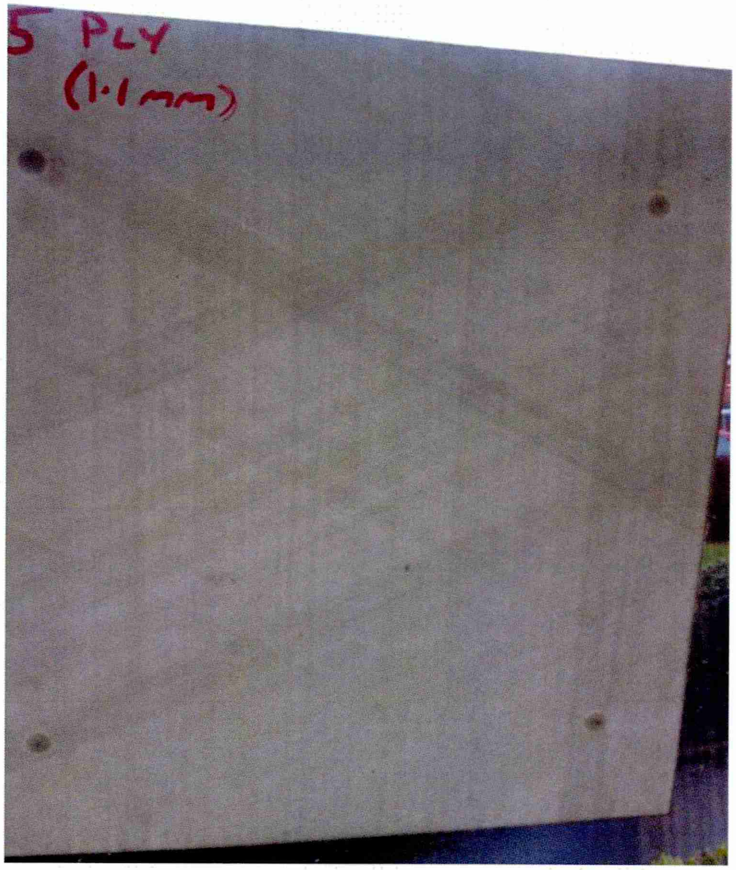


Figure 82: Fibre Distribution Of Fully Consolidated 5 Ply Laminate.

To create the top hat section when the sample had been heated to 190^0c and held at temperature for 5 minutes it was transferred to the top hat tool as shown in figures 83, 84 and 85, where it was pressed into a fully consolidated top hat section. When the press was closed with the thermoplastic material inside it, it was oil cooled to 80-90^0c before the tool was opened and the fully consolidated component removed.

Figure 83: Top Hat Tool In Press.

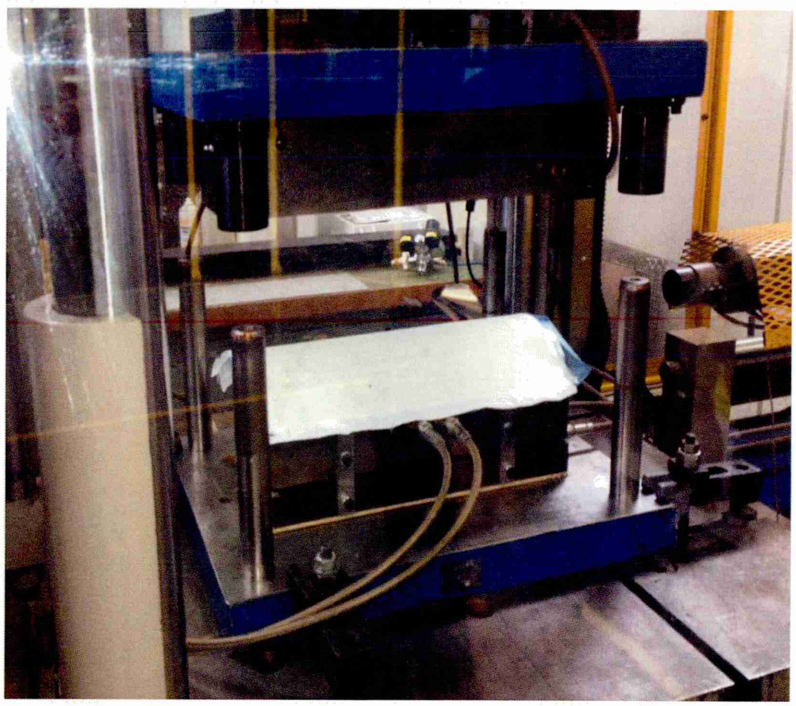


Figure 84: Top Hat Mould With Thermoplastic Material Placed On Top.

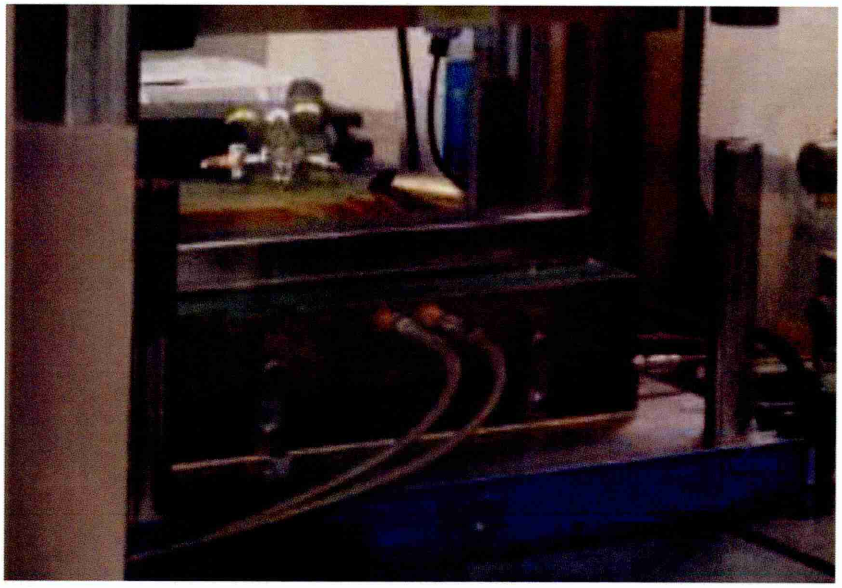
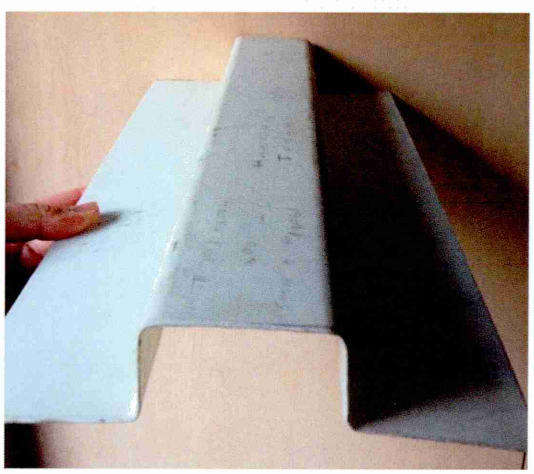


Figure 85: Top Hat Tool Close Up.

Figure 86 shows the top hat section fully consolidated, and a close up of the definition achieved with this material, once it had been removed from the mould. The top hat was examined for form, surface finish and quality as this was the first fully consolidated component produced using the lay up which would be automatically produced by the prototype machine. The pressed component carried the form of the top hat shape very well with no signs of warping or deformation of the component. The surface finish achieved shown in figure 86 was very good with a smooth shiny surface being produced.



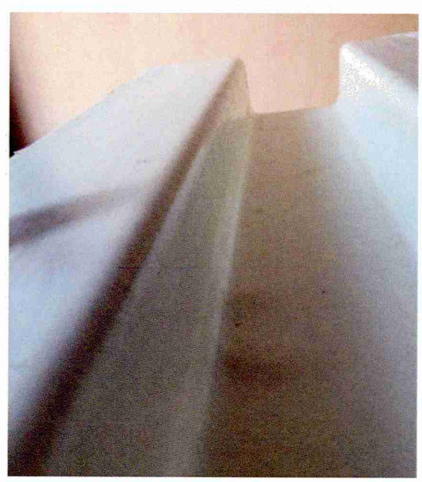


Figure 86: Fully Consolidated Top Hat (left) & Close Up Of Surface Finish (right).

7.2 Pressing of Spare Wheel Well:

Following the successful pressing of a top hat section I designed a scale model of a spare wheel well, with strengthening features and a deep drawn well. Figure 87 and 88 show the CAD drawings of the spare wheel well, which Joseph Rhodes used to manufacture a steel mould shown in figure 89.

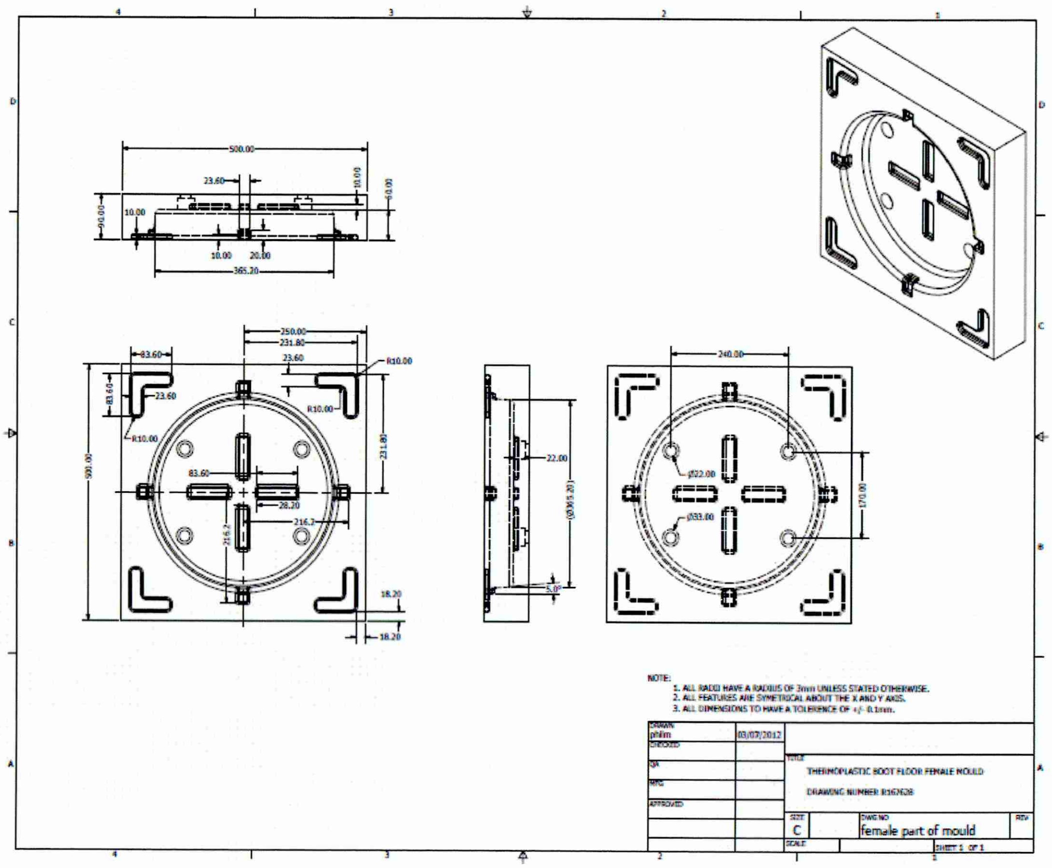


Figure 87: Female Spare Wheel Well Mould.

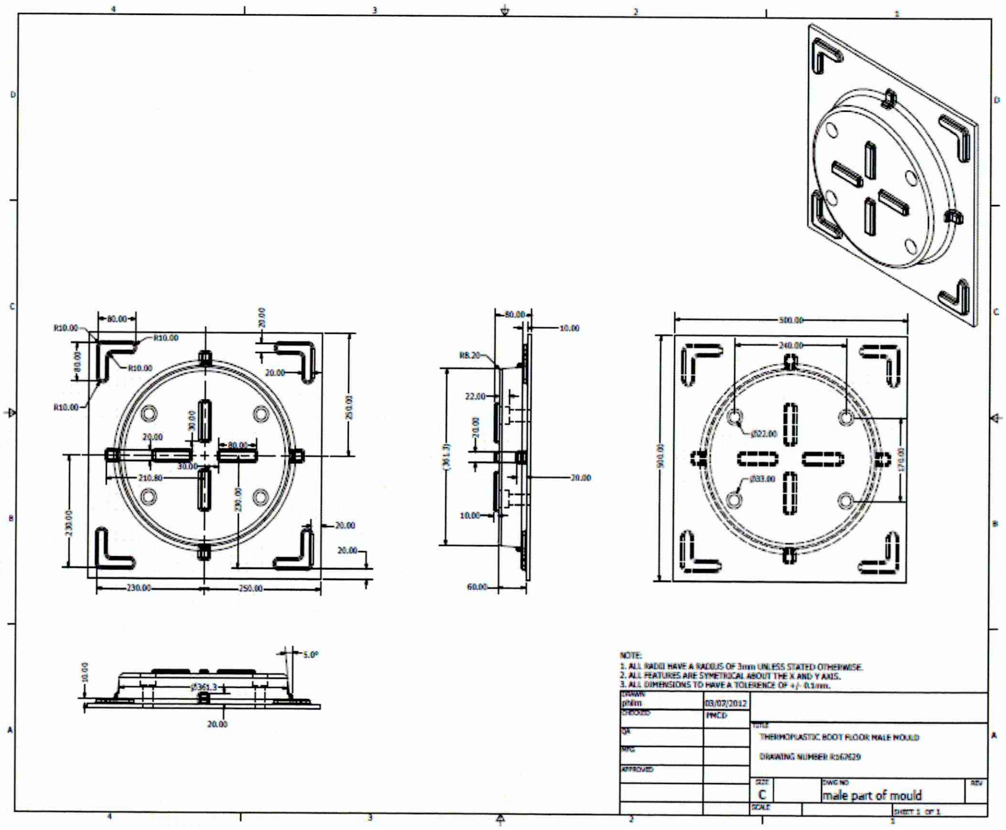
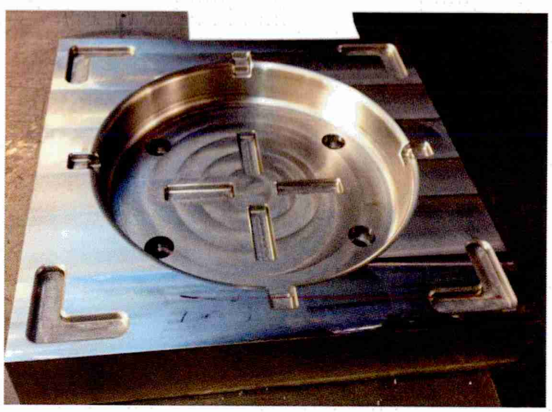


Figure 88: Male Spare Wheel Well Mould.



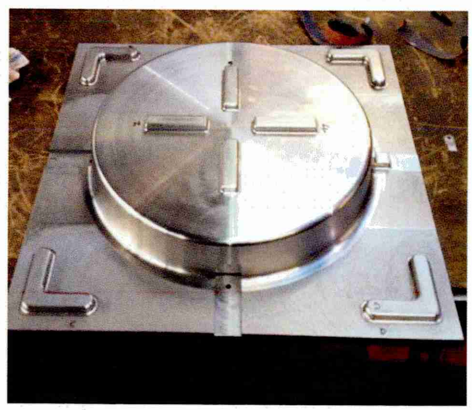


Figure 89: Spare Wheel Well Bottom Mould (left) & Top Mould (right)

To heat the thermoplastic material a purpose made oven was also made by Joseph Rhodes as shown in figure 90. The oven used 8 ceramic heaters controlled by a local PLC which was programmed to heat the thermoplastic material to 190^{o}c and hold it for 5 minutes before it would be transferred to the press for consolidation.


Figure 90: Thermoplastic Heating Oven Open (left) & Closed (right)

The thermoplastic material was placed onto the tray in the oven with a layer of PTFE at the top and bottom of the thermoplastic to provide surface contact as detailed in chapter 7.1. The material was then heated from ambient to 190 ^{o}c and held for 5 minutes before being swiftly transferred into the press to be pressed into the finished component.

After it has been held at temperature for 5 minutes the PTFE film is removed and the thermoplastic is then placed onto the mould in the press which was spray painted with a release agent so the plastic did not stick as shown in figure 91. The press then closes, remains closed for 5 seconds and opens to reveal a pressed component.

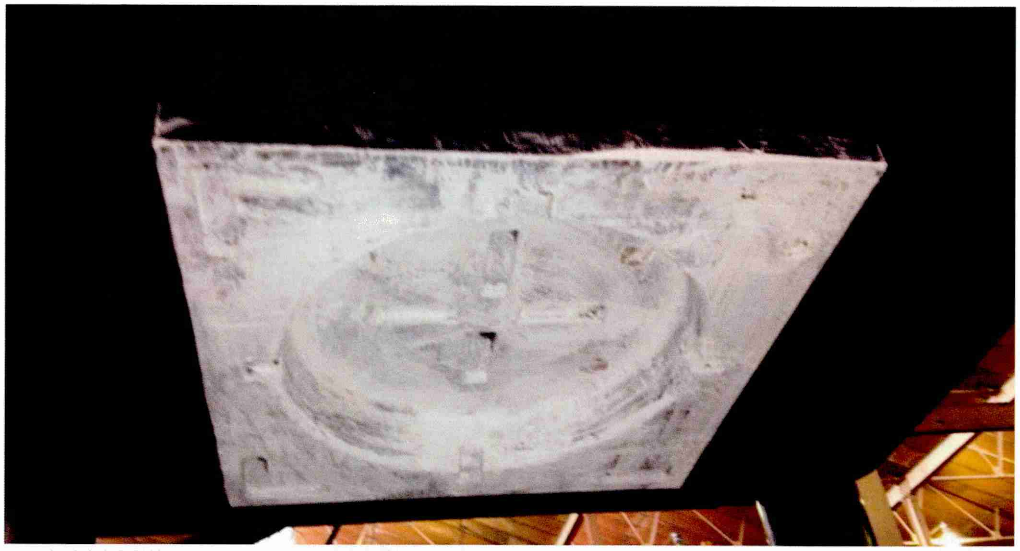


Figure 91: Female Mould (top), & Male Mould Painted With Release Agent (bottom).

When the component was removed from the mould it could be seen that the component achieved good definition on the features with the deep drawn well and strengthening ribs being achieved with a smooth finish. Figure 92 shows the pressed component after being removed from the mould. The thermoplastic material within the boundary of the tool achieved a good surface finish with well-defined features, while the thermoplastic material outside the tool boundary (scrap material) achieved bunching of the fibres as the deep drawn geometry was achieved. The material outside the tool boundary would be cut off and removed as waste material.

Figure 93 shows a close up view of the well-defined strengthening feature and the difference in finish between the pressed component and the waste material.

Figure 92: Pressed Spare Wheel Well Component.

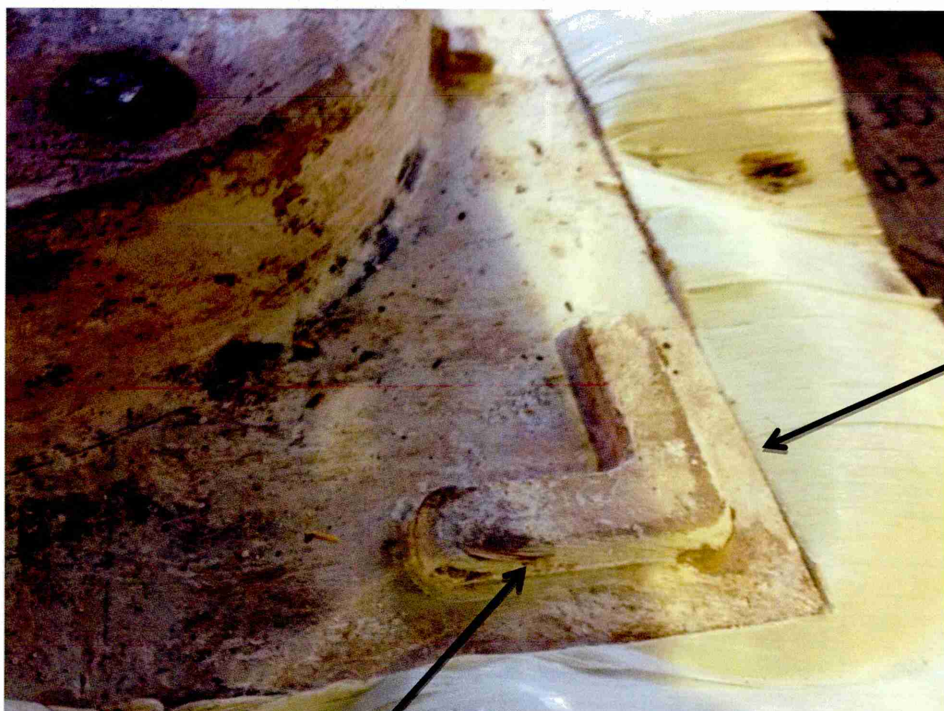


Figure 93: Pressed Component Strengthening Feature & Tool Boundary

The waste material around the edges of the component was then cut away using a slitter to give a well pressed spare wheel well as shown in figure 94.

Figure 94: Removing Waste Material From Pressed Component

Chapter 8 – Mechanical & Adhesive Fastenings.

An MSc project at Sheffield Hallam University entitled " Investigation of Mechanical Fastening Methods for Fibre Reinforced Automotive Parts" was supervised by the author (Gholampur 2012). This chapter will examine which methods were investigated, the results of the testing and conclusion to which method would be most appropriate. In addition to investigating mechanical fastening methods, adhesive methods were also investigated and compared against the mechanical methods.

The samples were tested using an Instron 3367 tensile testing machine (figure 95), and were tensile tested and peel tested to determine the failure load for each fastening method.

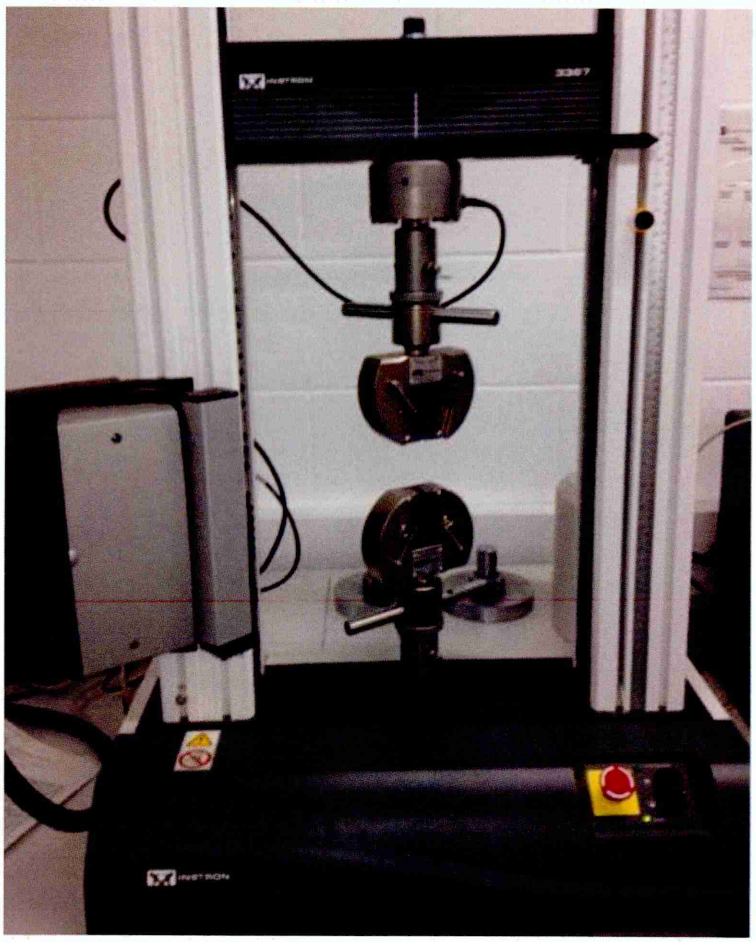


Figure 95: IInstron 3367 Testing Machine With Tensile Testing Rig.

To conduct the peel tests, a rig was made to secure them in place in the Instron testing machine. The samples were fastened to the rig (shown in figure 96) with 2 bolts at either side, before the samples were pulled apart to determine what failure load each sample had achieved.

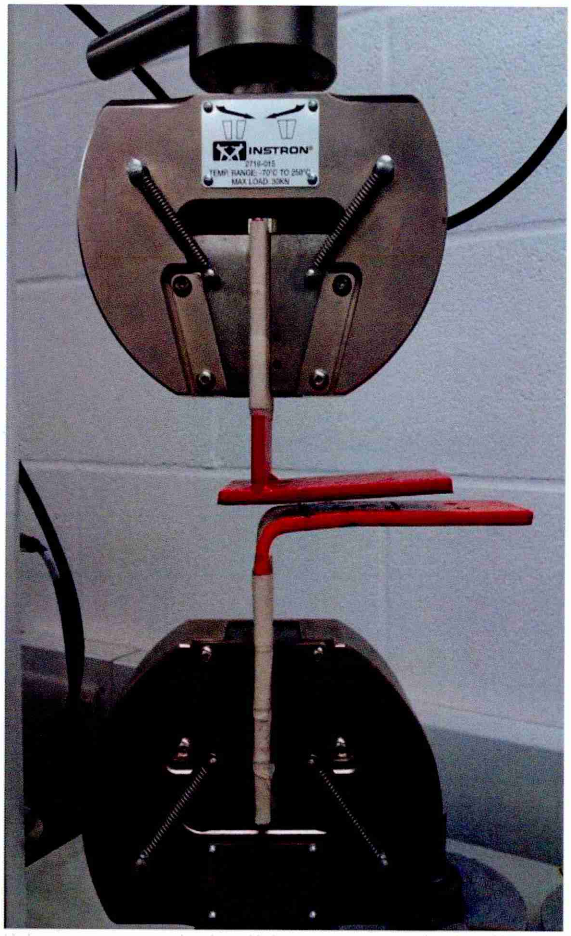


Figure 96: Peel Test Rig Mounted In Instron 3367

The samples were initially tested to ensure the fastening methods would be appropriate to secure a boot panel to the vehicle, while the boot was experiencing the maximum allowable payload.

The Nissan Qashqai has a maximum loading weight of 541Kg = 5307N using a safety factor of 2 = 10614N.

This load was used to calculate the quantity of each fastening method suggested to determine which method provides the best solution.

Adhesives were carefully selected to ensure they would bond polypropylene to metal, as the thermoplastic material would need to be secured directly to the metal structure of the vehicle.

8.1 Mechanical Fastening Methods:

The mechanical methods investigated included;

- A single M5 bolt

Figure 97: M5 Bolt

A single M5 bolt was chosen as it would allow the hole in the thermoplastic to be minimal (6mm hole) while ensuring the bolt could with stand the forces being applied to it.

- A single M5 bolt with a 35mm washer

Figure 98: M5 Bolt With 37mm Washer

The M5 bolt previously used had a 37mm washer added to provide a larger area of contact.

- A single 5mm rivet

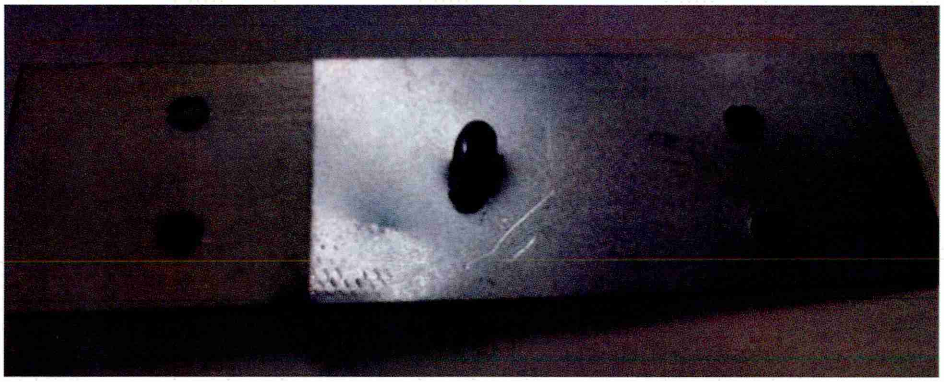


Figure 99: 5mm Rivet

A single rivet was chosen as it is quick and easy to install as well as being cheap, light weight (3g) and strong.

- A double rivet

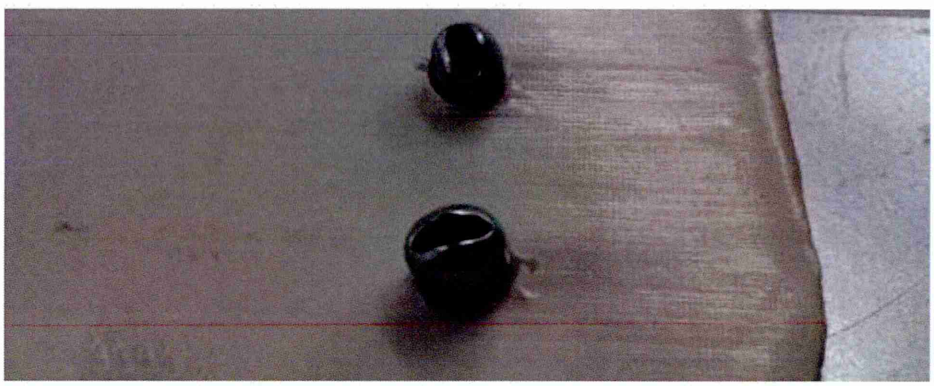


Figure 100: 5mm Double Rivet

A double 5mm rivet was chosen to determine if it would be a direct relationship to the single rivet.

- A 2 piece M5 knurled bolt

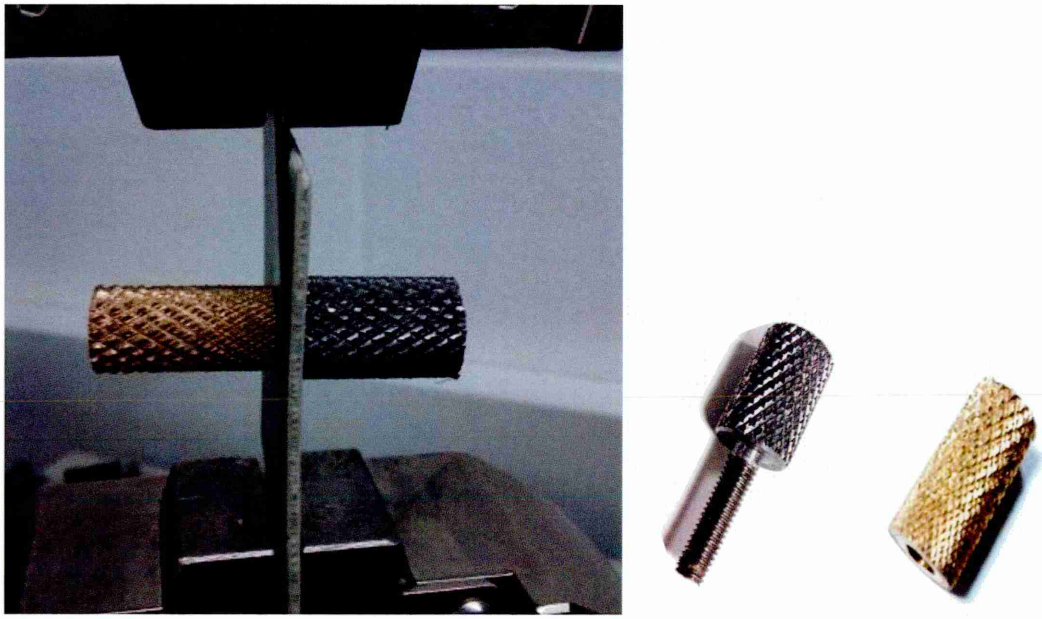


Figure 101: 2 Piece Knurled Bolt

A 2 piece knurled M5 bolt was chosen due to its ease of installation not requiring any tools.

- A square plate with 2 knurled bolts

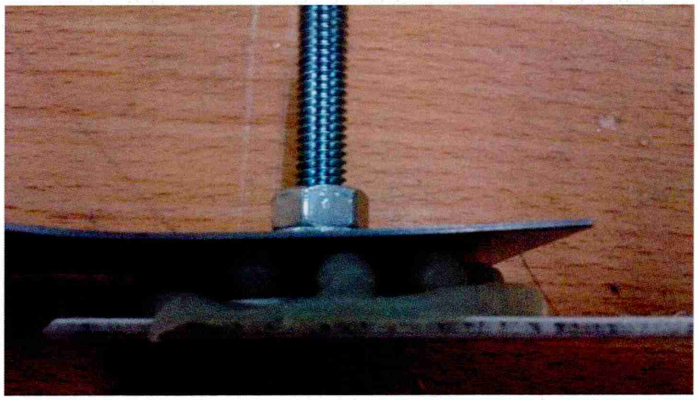
Figure 102: Square Plate With 2 Knurled Bolts.

A double M5 knurled bolt was chosen to determine if it would have an advantage over a single knurled bolt, in addition to the ease of installation.

8.2 Adhesive fastening:

The adhesive methods investigated included;

- Plexus adhesive from Bighead
  [http://www.bighead.co.uk/english/products/adhesives.asp]



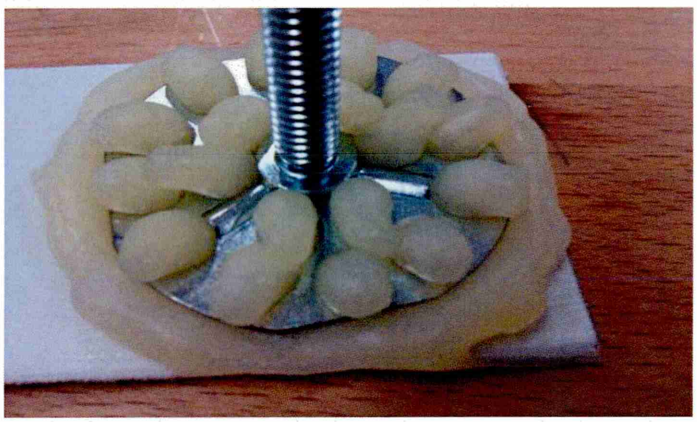


Figure 103: Plexus By Bighead

Plexus by Bighead was chosen as it is a combination of an adhesive and mechanical fastener, which provides a mechanical fastening method without the need to drill a hole through the thermoplastic.

- Gorilla Glue (General Purpose) [http://uk.gorillaglue.com/eng/glues/glue-list/1/8/gorilla-glue.html]

Figure 104: Gorilla Glue

Gorilla glue was chosen as it boasted characteristics such as being water proof, versatile and temperature resistant, as well as being suitable for both plastics and metals.

- Gorilla Super Glue [http://uk.gorillaglue.com/eng/glues/glue-list/1/15/gorilla-super-glue.html]

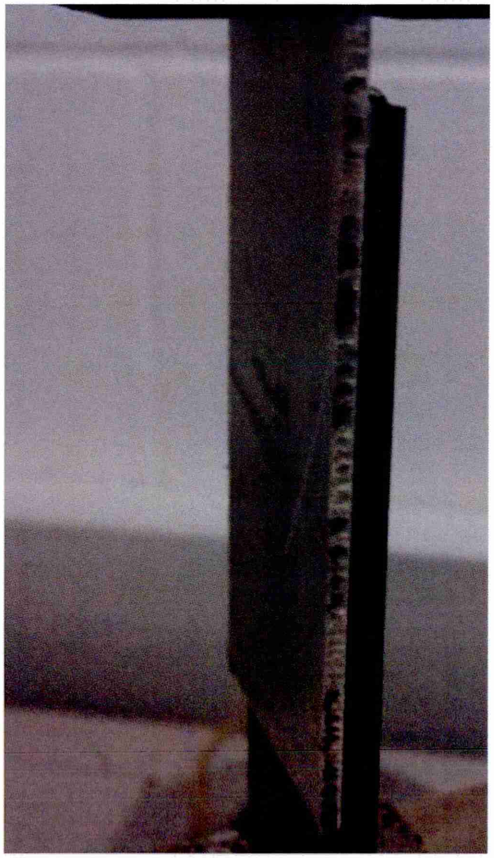


Figure 105: Gorilla Super Glue

Gorilla super glue was chosen as it has a quick drying time (30-60 seconds), and doesn't require any clamps to assist bonding.

- Loctite instant adhesive [http://www.loctite.co.uk/homepage.htm]

Figure 106: Gorilla Super Glue

- J-Fix (polyester resin) [http://www.flints.co.uk/acatalog/J-Fix_Cartridge_Epoxy_Acrylate.html]

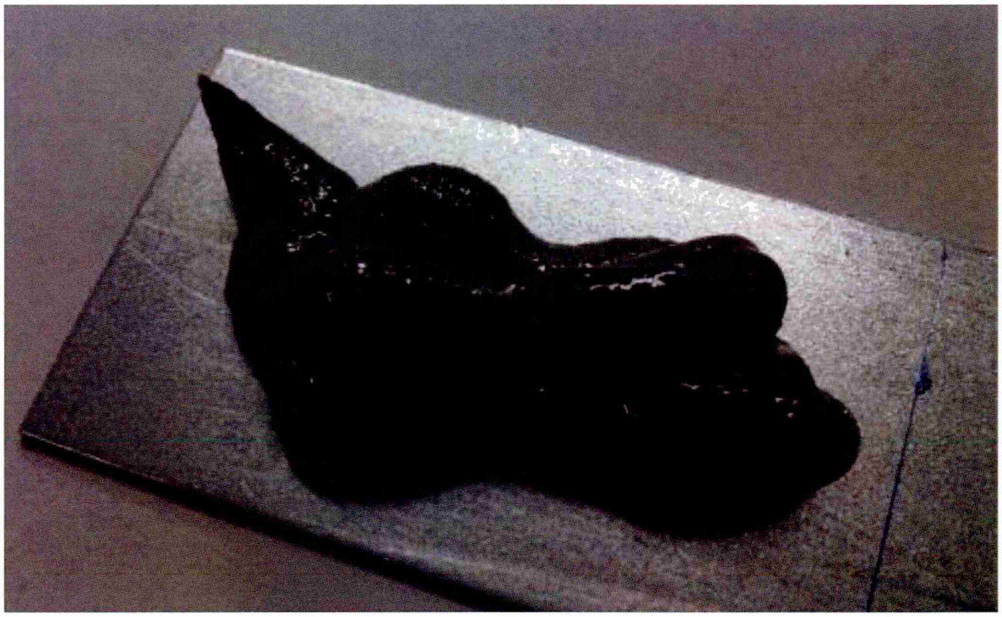


Figure 107: J-Fix

- Puraflex (Polyurethane adhesive and sealant) [http://www.everbuild-tecnic.co.uk/product/puraflex-40/]

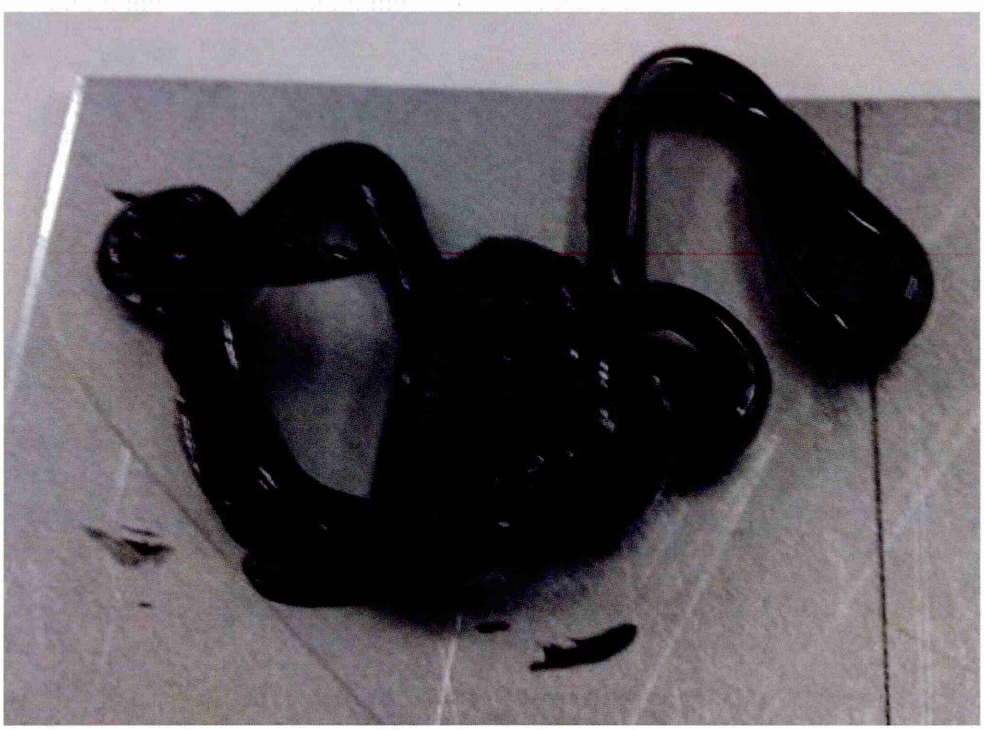


Figure 108: Puraflex

The results for the mechanical and adhesive tests are shown in table 14.

Table 14: Test Results For Mechanical And Adhesive Fastening Methods.

	Name of Samples	Failure Type	Tensile Test Load (N)	Peel Strength Test Load (N)
MECHANICAL FASTENING	SQUARE PLATE (5MM) *	Substrate	4354	938
	2-PIECE KNURLED BOLT (5MM) *	Substrate	3114	1098
	DOUBLE RIVET *	Substrate	2964	
	SINGLE RIVET *	Joint	1455	1335
	NORMAL BOLT WITH BIG WASHER (37MM)	Substrate	1156	-
	NORMAL BOLT	Substrate	2390	2034
ADHESIVE FASTENING	SUPER GLUE (LOCTITE - HENKEL) *	Joint	1000	318
	J-FIX	Joint	383	-
	GORILLAZ'S SUPPER GLUE	Joint	347	-
	BIGHEAD	Joint	267	-
	PURAFLEX	Joint	84	-
	GORILLAZ'S GENERAL PURPOSE	Joint	-	-

These show that adhesive samples failed much earlier than mechanical samples with Puraflex failing at only 84N in tensile testing, followed by plexus from Bighead which failed at only 267N. The best adhesive bonding agent was Loctite Super Glue which failed at 1000N in tensile tests and a failure load of 318N in peel tests. Loctite was the only adhesive which adhered to both metal and thermoplastic enough to perform peel tests on. The other adhesive fastening methods failed instantly in peel tests.

Mechanical methods outperformed adhesive methods with the lowest failure load exceeding that of loctite with 1156N. The strongest mechanical method in tensile testing was the square plate with a failure load of 4354N while the single rivet had the highest failure load in peel tests with 1335N.

8.3 Review of Mechanical Failure Modes:

Square plate (5mm):

The mechanical fastening with the greatest tensile testing failure load was the square plate which failed at 4354N however a much lower failure load was achieved in peel tests with only 938N. This would result in a need for 12 of these fastening methods to be used to achieve the failure load of 10,614N. With a mass of 135g for the square plate with double knurled bolts this would result in an additional mass of 1.62Kg, which would reduce the overall mass saving of the component from 2.56Kg to 0.94Kg.

2 piece knurled bolt (5mm):

The two piece knurled bolt had the second highest failure load in tensile tests with a load of 3114N being achieved, while 1098N was achieved in peel tests. This method achieved 150N more than the square plate in peel tests and weighed only 35g. as a result 10 2 piece knurled bolt fasteners would be required to secure the thermoplastic panel to the vehicle and achieve 10,614N failure load. This would in turn result in a mass of 350g, bringing the mass saving of the component down from 2.56Kg to 2.21Kg which is a much better mass saving than the square plate fastening method.

Double rivet:

The double rivet had a tensile failure load of 2964N with the peel test failure load missing so no comparison can be achieved on this method.

Single rivet:

The single rivet had a failure load of 1455N in tensile testing and a failure load of 1335N in peel tests. This method would require 8 rivets to be equi-spaced around the periphery of the panel weighing only 3g each. This is the lightest fastening method investigated and would result in an additional mass of 24g resulting in an overall mass saving of the panel being 2.536g. The single rivet samples failed due to the steel substraight plastically deforming around the rivet and detaching the joint, as shown in figure 109.

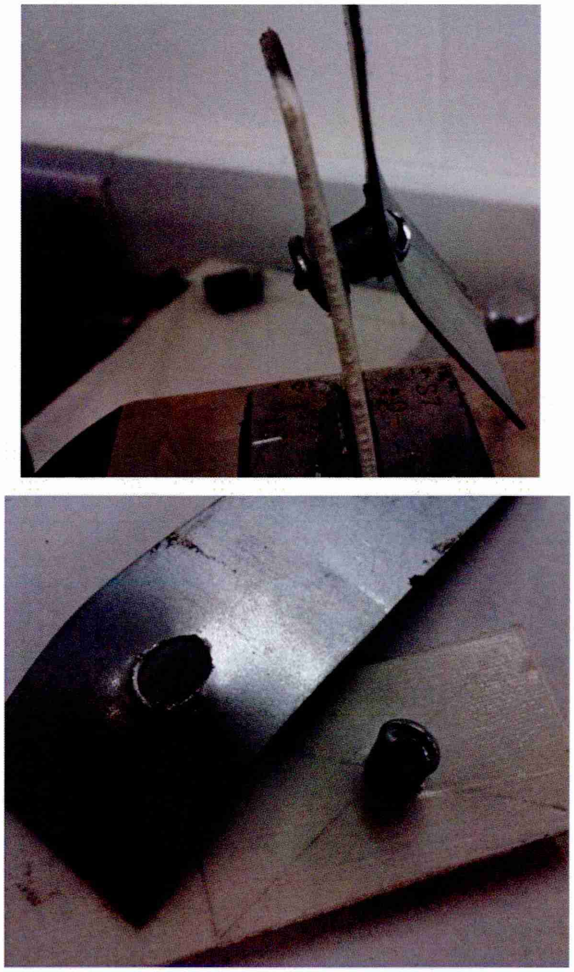


Figure 109: Single Rivet Failure Mode.

M5 bolt with 37mm washer:

The M5 bolt with 37mm washer had a failure load of 1156N in tensile testing, with no failure load in peel testing being recorded due to the thermoplastic failing at the joint to the peel testing rig as shown in figure 110. As this failure mode doesn't reflect the strength of the joint between the thermoplastic and the steel it has not been included in the MSc students report.

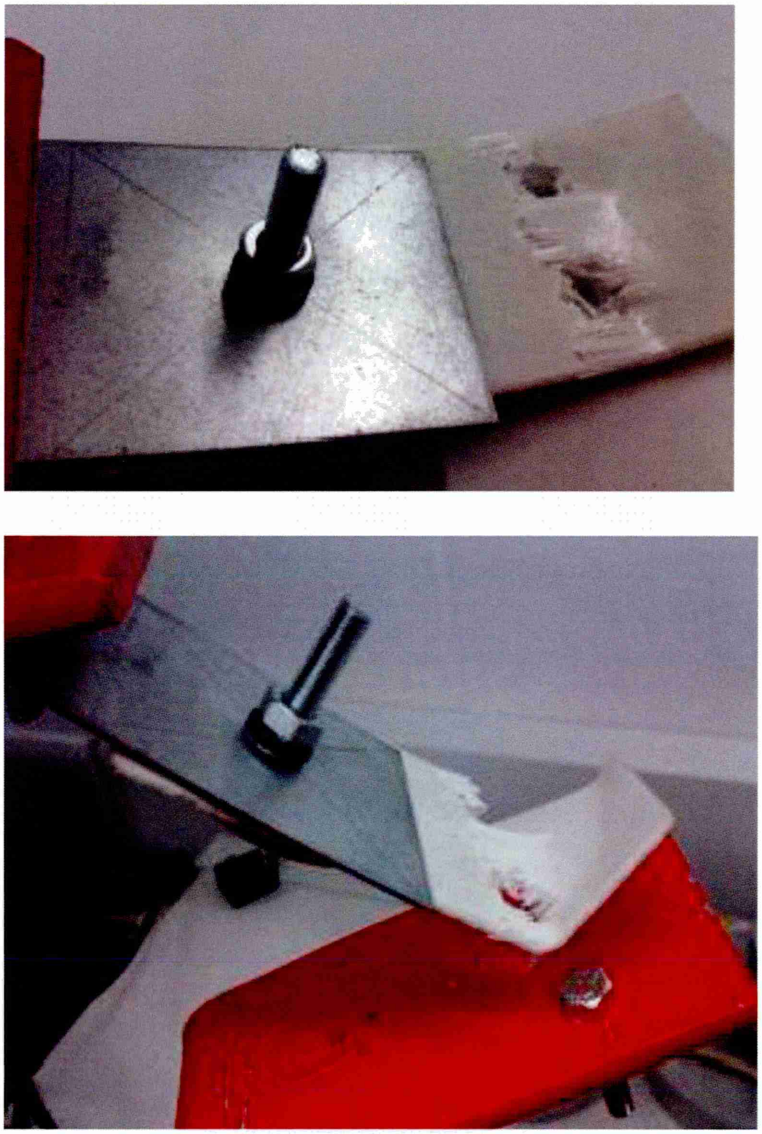


Figure 110: M5 Bolt With 37mm Washer Peel Test Failure Mode.

M5 bolt:

The M5 bolt had a failure load of 2390N in tensile testing and 2034N in peel testing. The vehicle panel would require 6 M6 bolts to secure it in place, which with a mass of 39g would result in an additional mass of 234g which would reduce the mass saving of the panel to 2.326Kg.

8.4 Conclusion:

From the study it can be concluded that a single rivet would be the most appropriate method of securing the panel to the vehicle, as the joint held within the thermoplatic very well, resulting in the steel frame of the vehicle failing before the joint in the thermoplastic. Rivets are light weight, cheap, quick and easy to secure. To secure the boot panel in place would require 8 rivets equally spaced around the periphery of the panel resulting in the thermoplastic component having an additional mass of 24g (negligable)

Chapter 9 – Prototype Machine.

9.1 Introduction:

The author applied for and was awarded a Government funded SMART grant to help towards the machine build costs to produce a fully functioning prototype machine. The grant was awarded to the sum of £192,000 which represented a 35% contribution. With this a prototype machine was manufactured based on concept 2, which proved the manufacturing process on a large scale.

The total estimated project costs came to £551,211 which consisted of labour, overheads, materials, capital equipment, travel and subsistence to meetings and exhibitions, patent application costs, thermoplastic material for trials, a boot pan mould for trials and an oven to heat the part consolidated sheets. Table 15 below shows a categorised break down of the project costs.

Table 15: Project Costs Categorised.

Category	Cost
Labour	£294,049
Overheads	£73,513
Materials	£23,575
Capital Equipment	£131,154
Travel and Subsistence	£3,334
Additional items	£25,586
Total cost	£551,211

The design team at Joseph Rhodes Ltd produced detailed drawings of the concept machine for manufacture based on guidance and specifications provided to them by the author.

9.2 Stage 1 – Material widening

Stage 1 created a roll of inline fibre reinforced material to a width of 1010mm by joining 3 rolls of 343mm wide material together using a double hot air welding machine then trimming it to an exact width of 1010mm before coiling the material on a collection roller as shown in figure 111.

The cost to produce this stage was £90,445 which was a lot more than the estimated cost in chapter 5 of £70,000. The double hot air welding machine was a lot more than estimated with it costing £62,345 instead of £50,000, this was because the machine was a bespoke machine which was made for our specific application. The control panel and motors for stage 1 also came in above budget at £13,100 instead of £10,000, which with the increase in the hot air welding machine and the addition of safety chucks and manual brakes put stage 1 £21,445 above budget, however the actual cost of stage 1 came in £20.445 above budget due to a £1,000 saving on the fabrication costs.

Table 16: Stage 1 – Actual Cost Vs. Estimated Cost

Stage 1 costs	Actual Cost	Estimated cost
Safety Chucks and manual brakes	£6,000	-
Hot air welding machine	£62,345	£50,000
Control panel & motors	£13,100	£10,000
Fabrications	£9,000	£10,000
Total	£90,445	£70,000

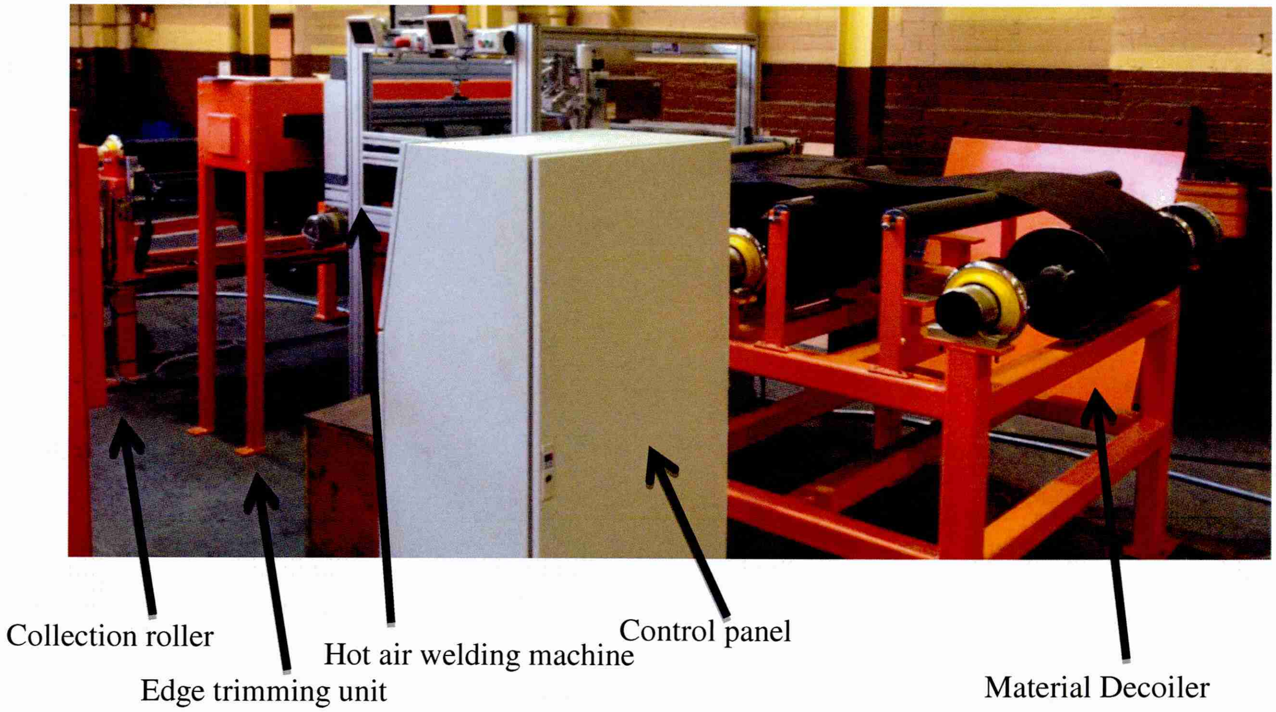


Figure 111: Stage 1 - Material Widening.

The rolls of raw material 343mm wide are loaded into the safety chucks on the material decoiler, with the second roll overlapping the edge of the first roll by 9mm, and the third roll over lapping the edge of the second roll by 9mm also. Each safety chuck is mounted with a manual brake so the operator can apply more or less resistance to the rolls of material if they are running too slack or too tight. These three rolls are then fed into the double hot air welding machine where the hot air outlet lowers into position underneath the top layer and above the bottom layer, so as to exhaust hot air at 600^{o}c at a flow rate of 150L/min onto the bottom surface of the top layer and the top surface of the bottom layer making the plastic melt. The compression roller of each welding head is situated directly behind the hot air outlet and compresses the layers of material together to form a weld. The compression rollers run at a rate of 40m/min as achieved in trials in chapter 4 – feasibility study. Figure 112 shows the double hot air welding machine and the position of the hot air outlet with respect to the compression roller, while figure 113 shows the position of the first and second welding units.

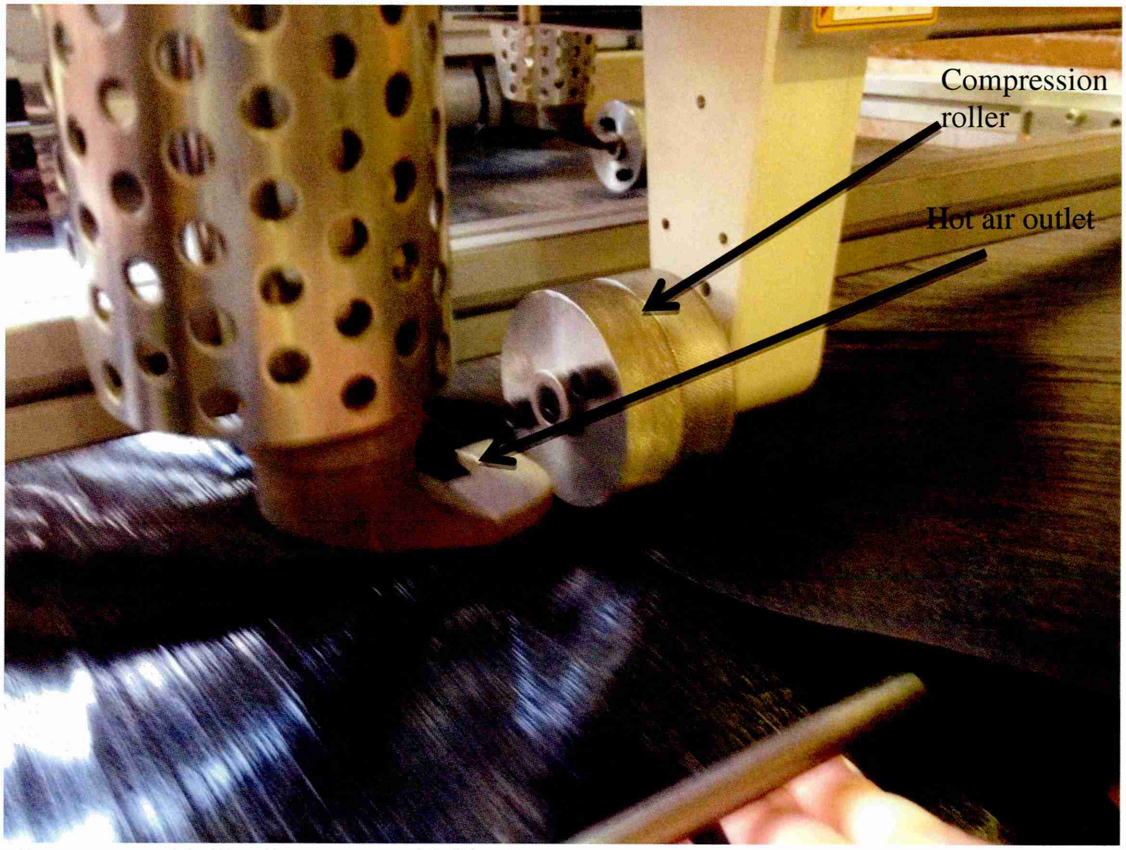


Figure 112: Stage 1 – Double Hot Air Welding Unit.

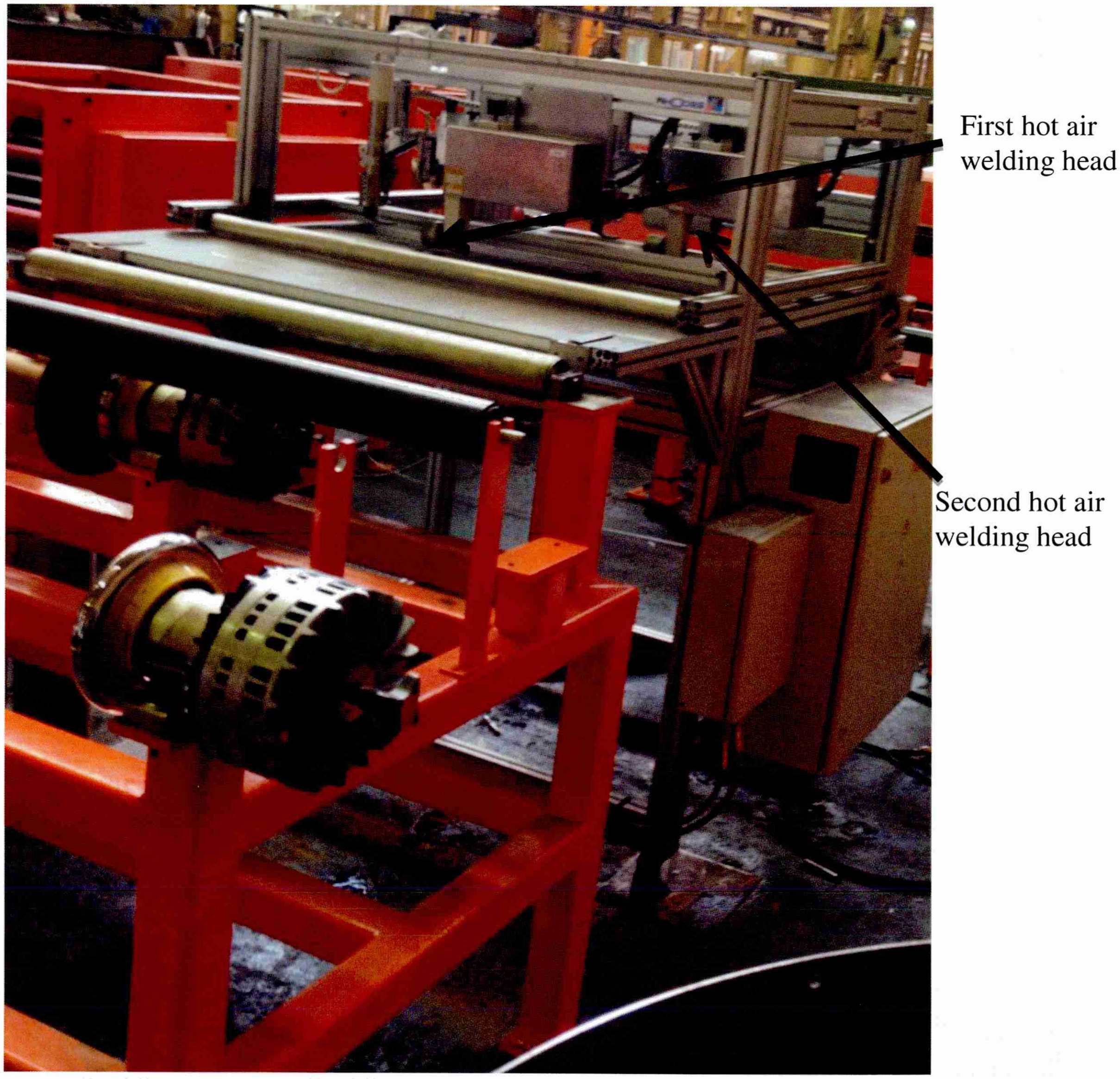


Figure 113: Stage 1 Double Hot Air Welding Unit.

Once the material has been joined together to form a width of material 1011mm wide the material passes through an edge trimming unit which trims the material to 1010mm wide, eliminating any deviations in the raw material which would form the tape greater than 1011mm wide in the hot air welding unit. The edge trimming unit does this by using 2 circular cutting discs mounted onto a motor driven shaft. The knives rotate at faster than the linear speed of the material, thus acting like a continuous pair of scissors. The blades are set to have 1010mm separation between them but the position of the blades is also adjustable on the shaft by loosening the grub screws and repositioning the blades. Figure 114 shows the edge trimming unit and material entry point and figure 115 shows the edge trimming blade.

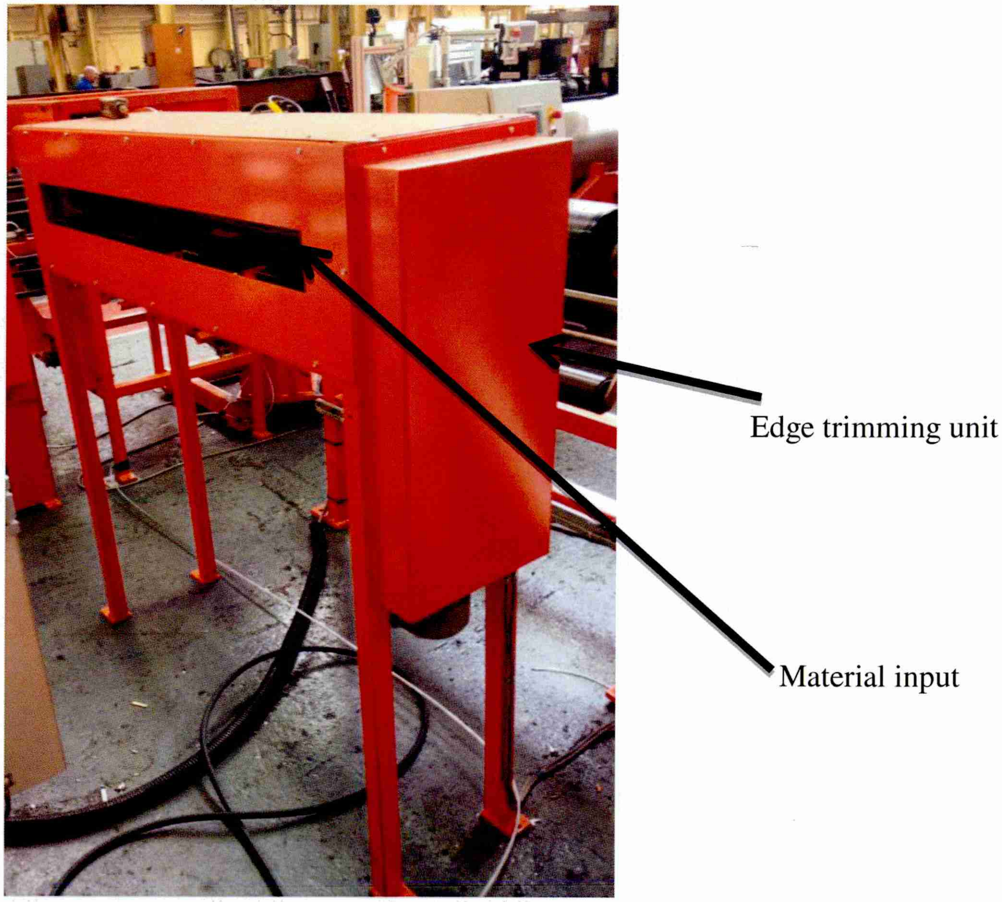


Figure 114: Stage 1 – Edge Trimming Unit

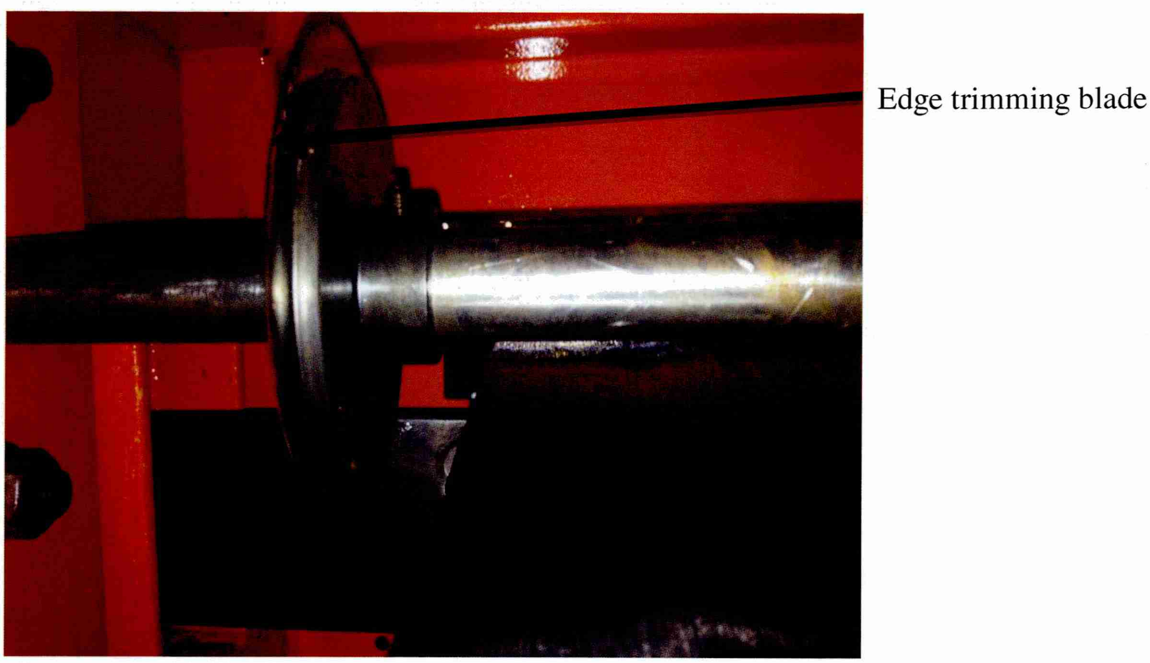


Figure 115: Stage 1 – Edge Trimming Unit

After the material has been trimmed to 1010mm wide it is collected on a material collection roller (figure 116) which is again fitted with safety chucks, one of which is fitted to a motor. This motor drives the roll round, collecting the material as it is being produced. The material wraps under the material tensioning bar which is coupled up to a potentiometer.

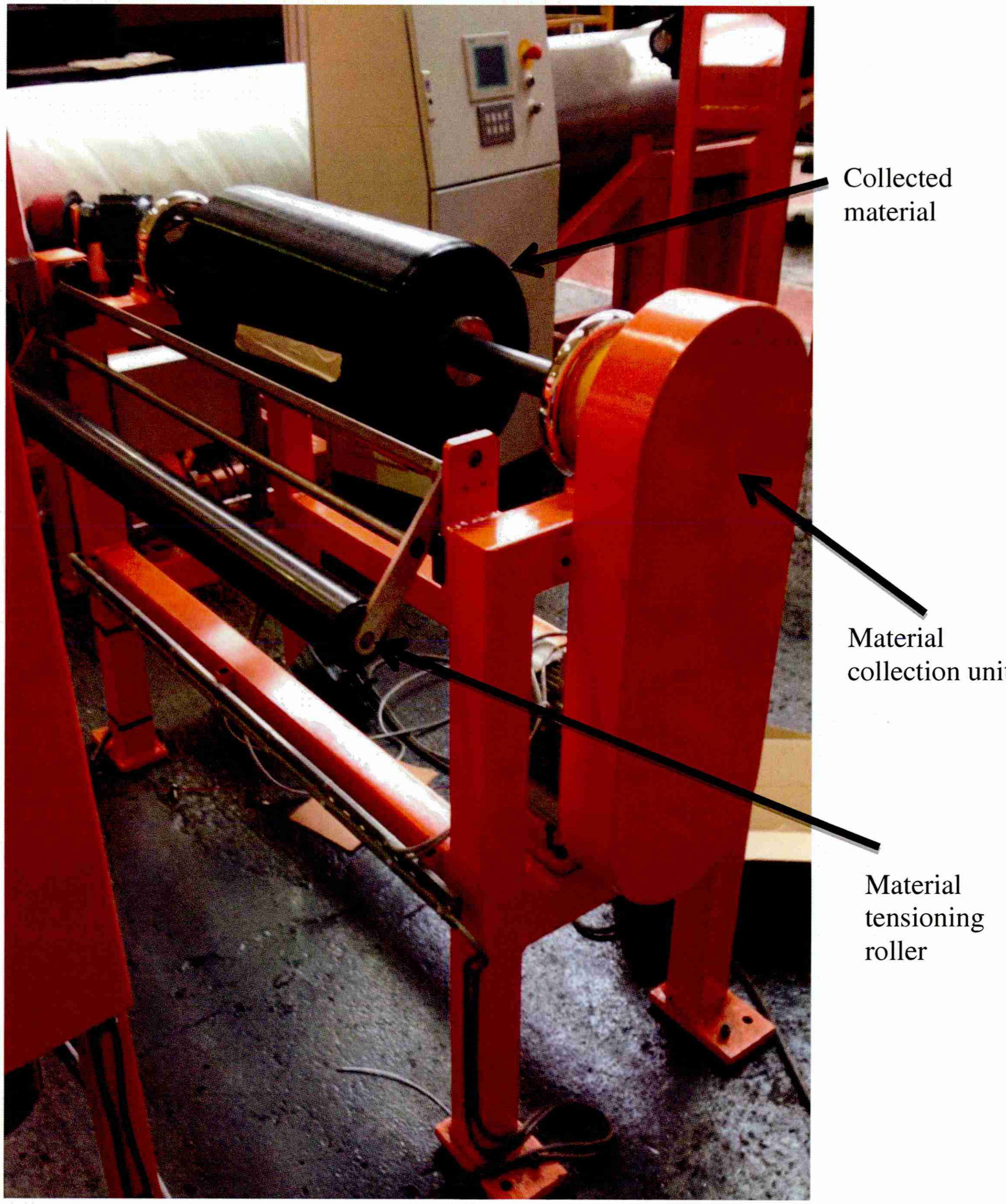


Figure 116: Stage 1 – Material Collection Unit

Stage 1 is controlled by a control panel (figure 117) which controls the double hot air welding unit, the edge trimming unit, and the material collection unit. The speed of the material collection roller needs to reduce the more material it collects as the outer diameter of the material increases. This is controlled by the potentiometer in the tension roller so, if the tension roller is lifted too high, there is too much tension in the material, and the control panel tells the motor to slow down, equally so, if the roller drops too low, there isn't enough tension in the material and the control panel tells the motor to speed up.

Figure 117: Stage 1 – Control Panel

9.3 Stage 2 – Tube Forming

Stage 2 creates the off axis 2 ply sheets of thermoplastic material by creating a continuous tube, cutting it to length and compressing it into a flat sheet. The tube is welded using a single hot air welding machine, and is driven along the mandrel using a belt drive (as shown in figure 118). The tube is then cut to length using a travelling shear and compressed into a 2 ply flat off axis sheet of material using compression rollers (as shown in figure 119), all of which is controlled by a control panel (figure 120). The control panel for stage 2 controls the hot air welding machine, the speed of the belt drive, the operation of the travelling shear, and the compression rollers.

The cost to produce this stage was £73,080 which was very close to the estimated cost in chapter 5 of £75,000. The greatest cost in stage 2 was the hot air welding machine which came in a little higher than the estimated cost of £25,000 at £27,580. The control panel and motors, and materials came in over budget as well and with the need for some unexpected safety chucks and manual brakes put us £14,980 over budget, however due to the fabrications costing less than half of the estimated price, the total manufacture of stage 2 came in £1,920 below budget at £73,080. The fabrications came in much less than the estimated price due to the frame work being fabricated in house and the mandrel being machined in house.

Table 17: Stage 2 – Actual Cost Vs. Estimated Cost

Stage 2 costs	Actual Cost	Estimated cost
Safety Chucks and manual brakes	£1,500	-
Hot air welding machine	£27,580	£25,000
Materials	£15,500	5,000
Control panel & motors	£15,400	£15,000
Fabrications	£13,100	£30,000
Total	£73,080	£75,000

Figure 118: Stage 2 – Tube Forming Part 1

Figure 119: Stage 2 – Tube Forming Part 2

Figure 120: Stage 2 Control Panel

The material is taken straight from stage 1 where it is cut to a width of 1010mm and placed into the safety chucks with a manual brake on the material decoiler. It is then pulled through the material tensioning unit to apply tension before it is wrapped around the mandrel at 30 degrees as shown in figure 121. The mandrel is secured on the mandrel frame at one end, with the other end floating so the material can be formed and continue to progress along the mandrel without coming to a stop as shown in figure 122.

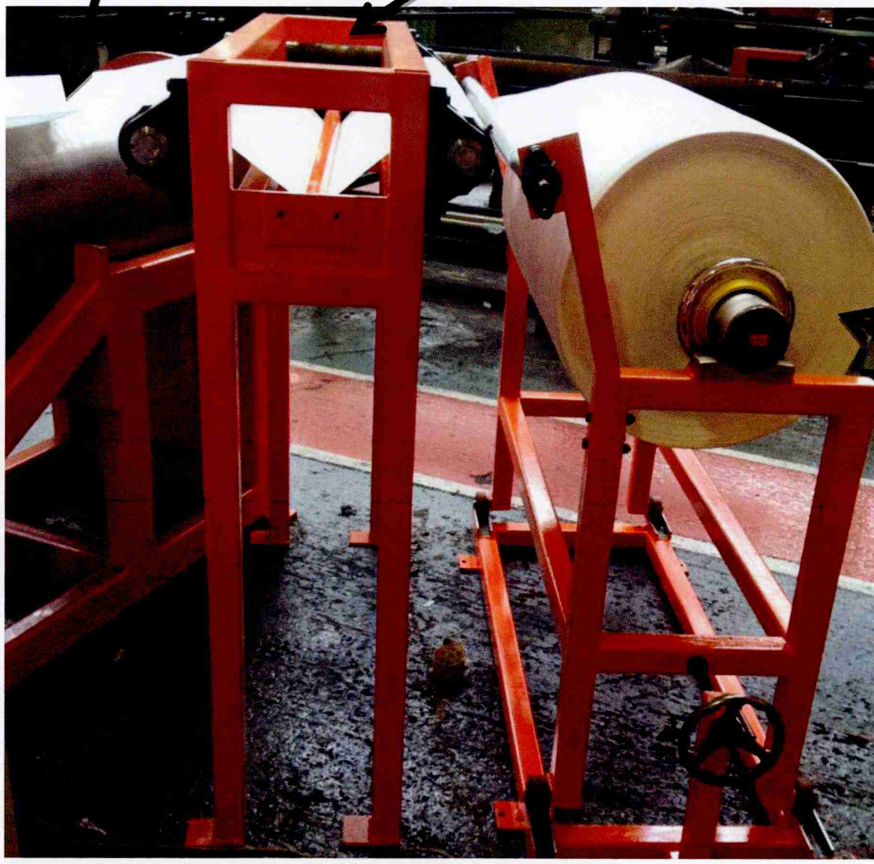


Figure 121: Stage 2 – Material Decoiler

Figure 122: Stage 2 - Mandrel

Once the material has been wrapped around the mandrel with the receeding edge of the first wrap overlapping by 10mm the proceeding edge of the second wrap , the hot air welding unit lowers into position so the hot air outlet is inbetween the top and bottom layer of material. When the air outlet is in this position it exhausts air at 600°c at a flow rate of 150L/min onto the bottom surface of the top layer of material and the top surface of the bottom layer of material which melts the two surfaces so they can weld together. The compression rollers situated behind the hot air outlet nip the material immediately after it has passed the hot air outlet and forces the two layers together creating a weld. These rollers run at 30m/min linear speed which is 10m/min less than the trials conducted in chapter 4 – feasibility study, this is to ensure that the material does not warp or twist so the overlap remains a constant 10mm. Figure 123 shows the material being wrapped around the mandrel with the proceeding edge wrapping over the receding edge with a 10mm overlap at the hot air outlet region.

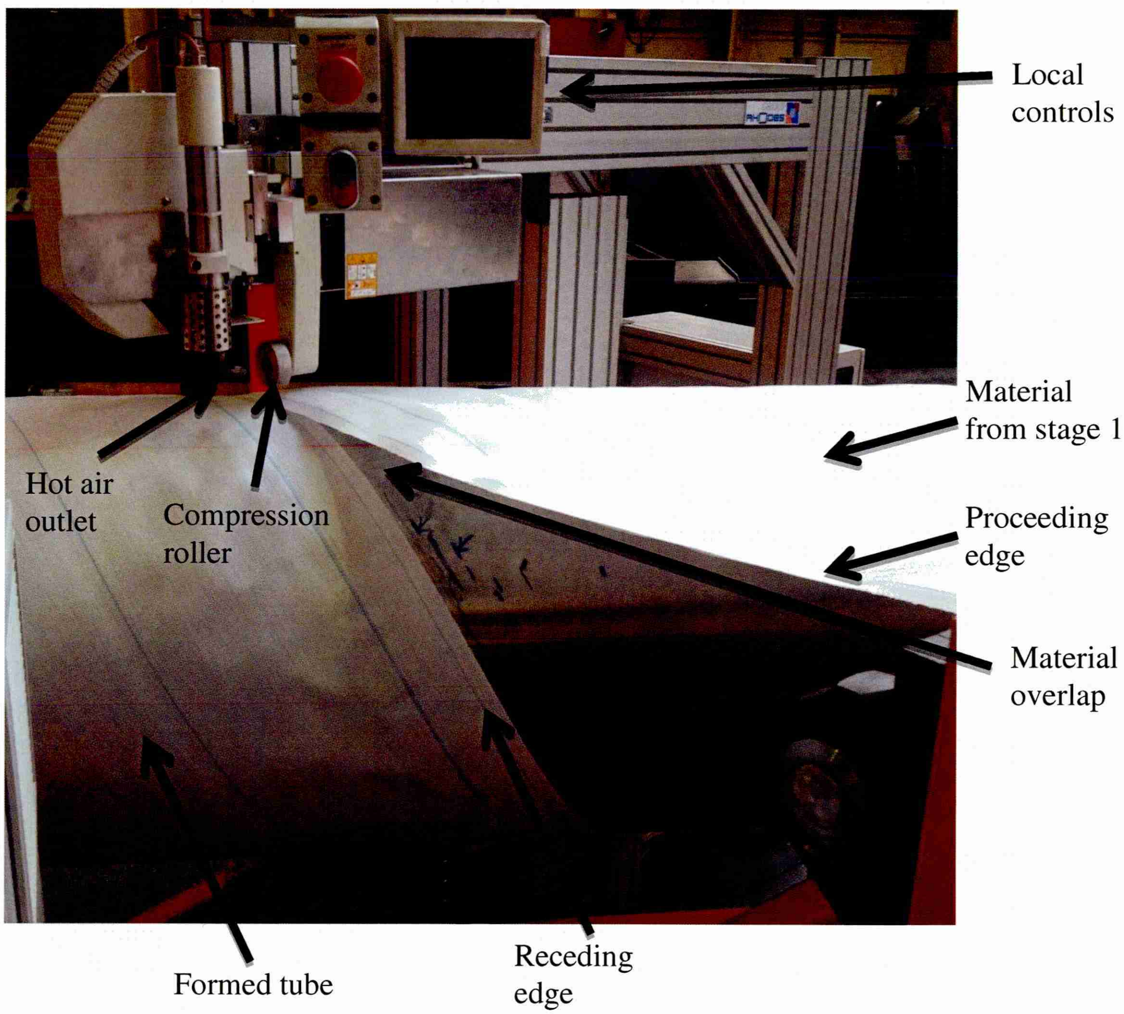


Figure 123: Stage 2 – Hot Air Welding Unit

After the tube has been formed it progresses down the mandrel via the belt drive, which is located on the mandrel frame as shown in figure 124. The belt drive pushes the now formed tube with a rubber backed belt at the input angle (in this case 30 degrees) and at the same speed as the hot air welding unit. This helps drive the tube along the mandrel to the travelling shear, without asking too much of the compression rollers on the hot air welding unit.

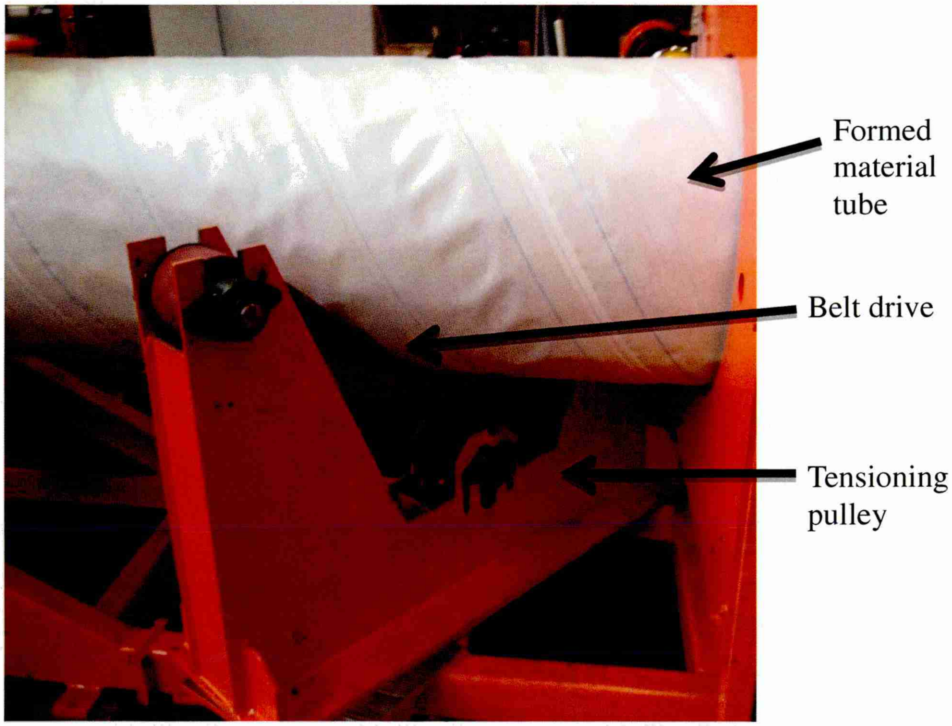


Figure 124: Stage 2 – Belt Drive

As the tube continues down the mandrel it comes to the travelling shear, which cuts the tube into a given length. The travelling shear sits over the mandrel and cuts the tube on the mandrel face using 8 equally spaced cutting blades. This is so the tube it cut through $1/8^{th}$ of a rotation to reduce the over all length of the mandel, and stage. Figure 125 shows the tube entering the travelling shear with 8 blades positioned equally around the perifery of the travelling shear.

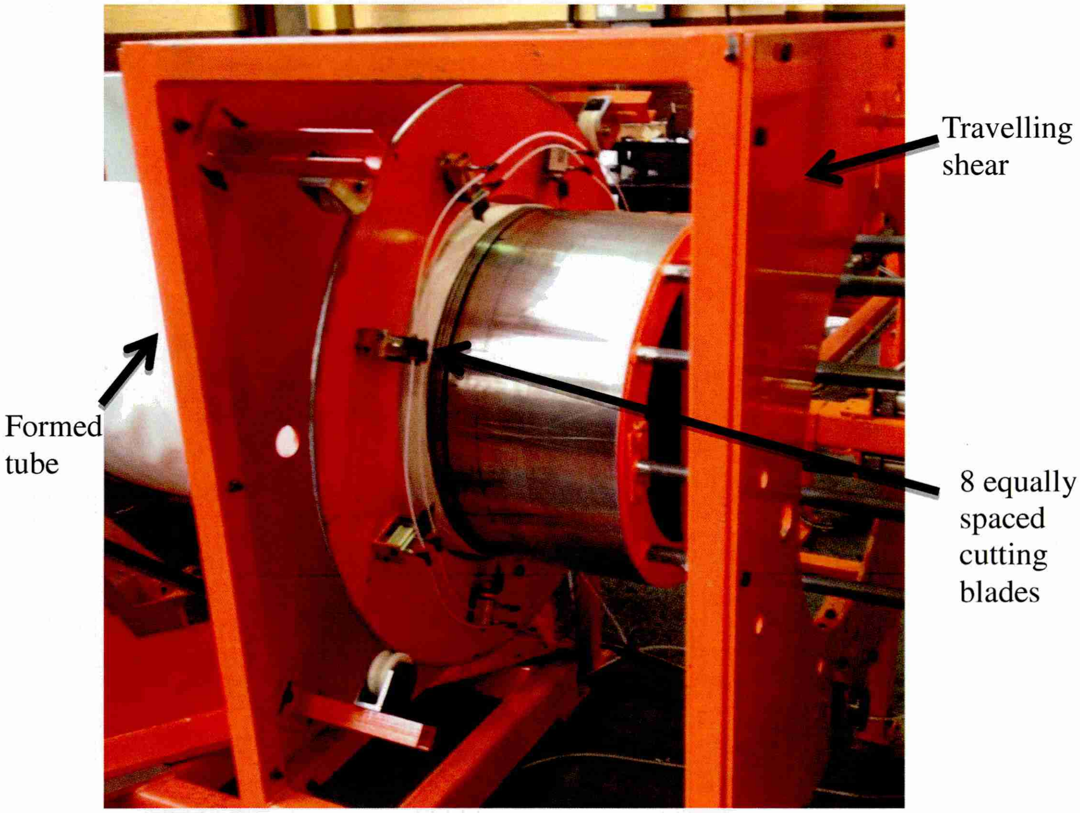


Figure 125: Stage 2 – Travelling Shear

The tube is then pushed along the guides at the end of the mandrel by the proceeding continuous tube as that travels through the travelling shear prior to being cut, the cut length of tube continues to be pushed until it contacts the top and bottom drive rolls of the compression roller unit. These rolls grip the tube and pull it through the compressoin roller unit, gradually compressing it into a 2 ply flat sheet. The drive rolls run at a faster speed than the tube being formed so it is pulled out of the way faster than the next tube is being produced. Figure 126 shows the compression roller unit gradually compressing the material as it progessses through the unit until it is fully compressed into a 2 ply flat sheet as shown in figure 127.

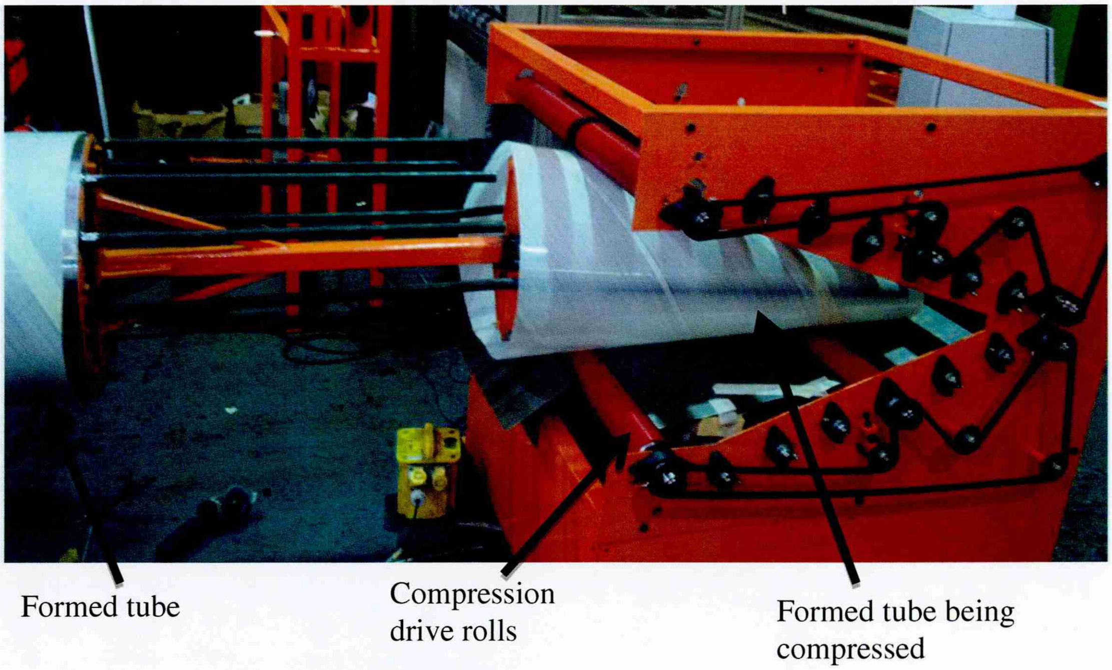


Figure 126: Stage 2 – Compression Rollers.

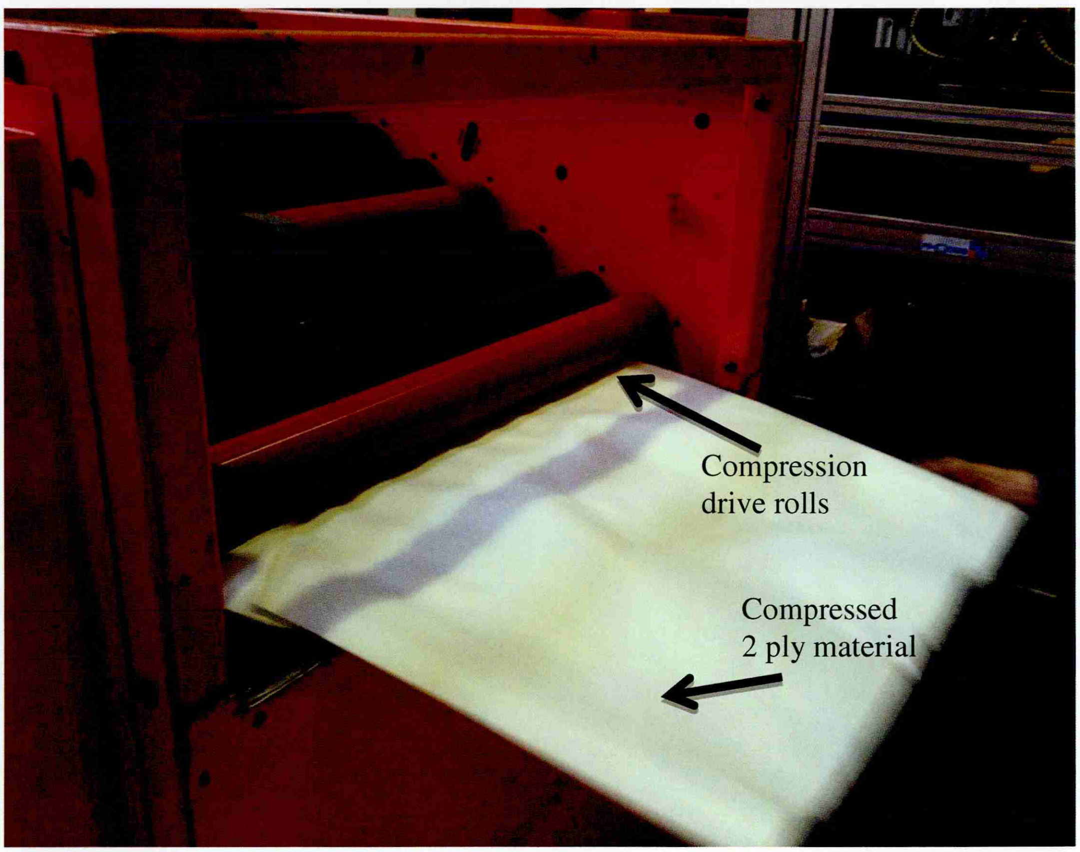


Figure 127: Stage 2 – Compressed Material Exit Point.

9.4 Stage 3 – In Line Sheet Production

Stage 3, which cuts the lengths of unidirectional materal into the required length consisted of a material decoiler like that used in stage 2, and a guillotine which was modified to be controlled by two pneumatic cylinders (figure 128). In the design process in chapter 6 stage 3 also had a set of driven nip rollers which would index the material a given length before the guillotine blade would be actuated. Due to this prototype only proving process on a large scale the company decided as a cost saving exercise to remove the operation of stage 3 from the control panel to make the controls more simplistic and less expensive. It was decided by the company that the feeding of the material in stage 3 would be manually operated with the material being fed into the guillotine directly from the material decoiler in stage 2.

Stage 3 was the cheapest stage to produce with the guillotine being purchased second hand at only £325, and was modified with pneumatic cylinders to actuate automatically costing a further £400 resulting in a cost for the guillotine unit of only £725. Stage 3 uses the same material decoiler as that used in stage 2 as this prototype was to prove that each process works. The total cost for stage 3 was £725 which is much less than the estimated cost of £25,000 in chapter 5, coming in with a cost saving of £24,250. This is a result of being able to source a guillotine second hand and simplifying stage 3.

Table 18: Stage 3 – Actual Cost Vs. Estimated Cost

Stage 3 costs	Actual Cost	Estimated cost
Guillotine	£325	£10,000
Pneumatic cylinders	£400	-
Control panel & motors	-	£10,000
Fabrications	-	£5,000
Total	£725	£25,000

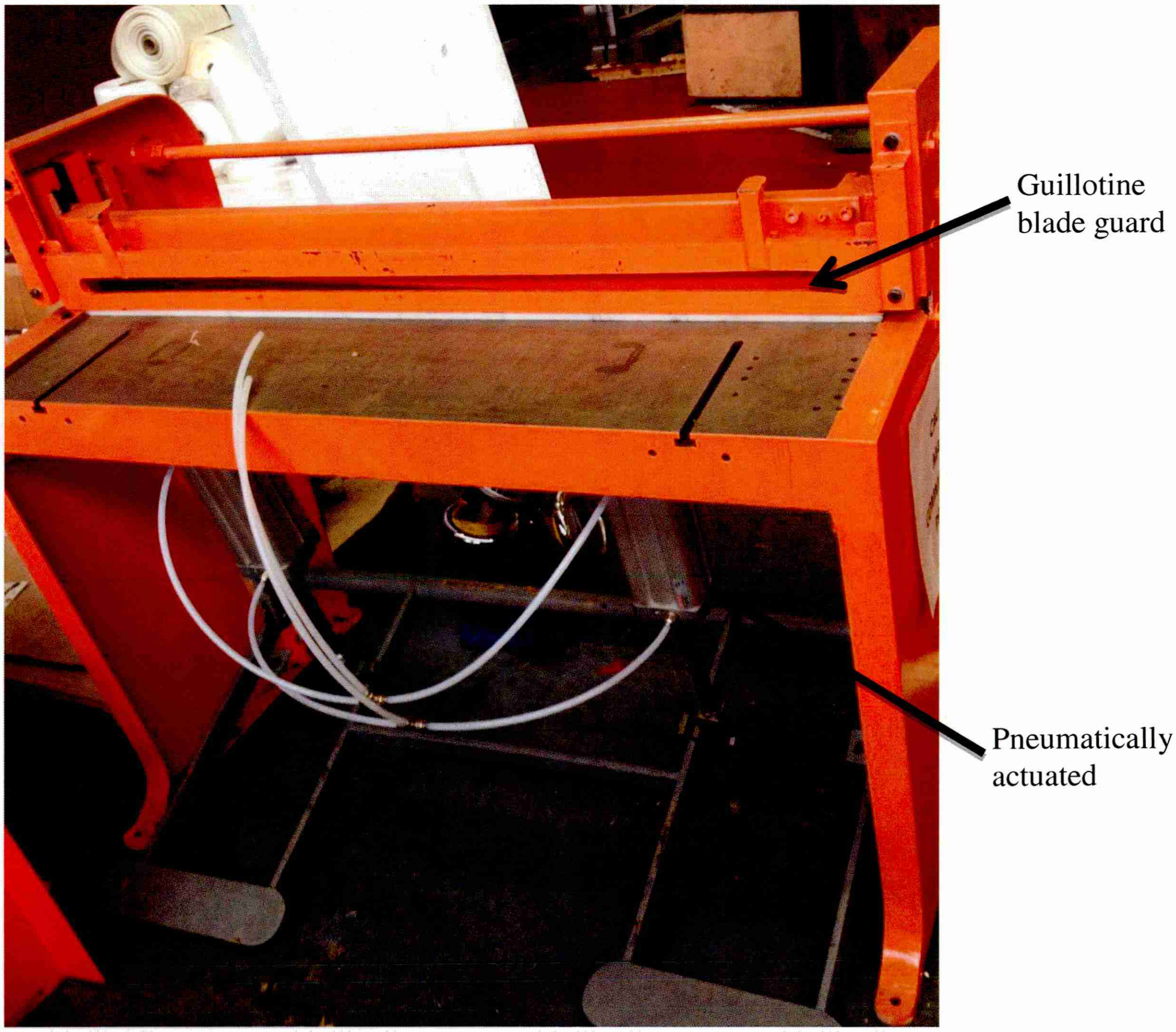


Figure 128: Stage 3 – Guillotine.

9.5 Stage 4 – Part Consolidation

Stage 4 stakes 5 layers of material together, (2 x 2 ply compressed tubes from stage 2, and 1 x unidirectional sheet from stage 3) to form a part consolidated laminate. This is achieved by manually placing the layers in the correct orientation on the table top of stage 4, aligning the layers up so all 5 layers are square to each other and pushed against the side and back of the table. The ultrasonic welding units are pneumatically lowered using the twist switches on the sides of the table, then two welds are performed by switching the ultrasonic units on with the 2 red push buttons in the corners as shown in figure 129. Each ultrasonic welding unit is lowered using an air cylinder which is part of the unit itself. Once the unit has been lowered so the welding horn is in contact with the material it can be turned on so the frequency produced by the welding unit is bounced back from the table underneath which acts as an anvil, thereby exciting the plastic molecules and creating a weld.

Table 19: Stage 4 – Actual Cost Vs. Estimated Cost

Stage 4 costs	Actual Cost	Estimated cost
Ultrasonic welding units	£11,980	£20,000
Materials	£1,000	-
Fabrications	£1,500	£2,000
Total	£14,480	£22,000

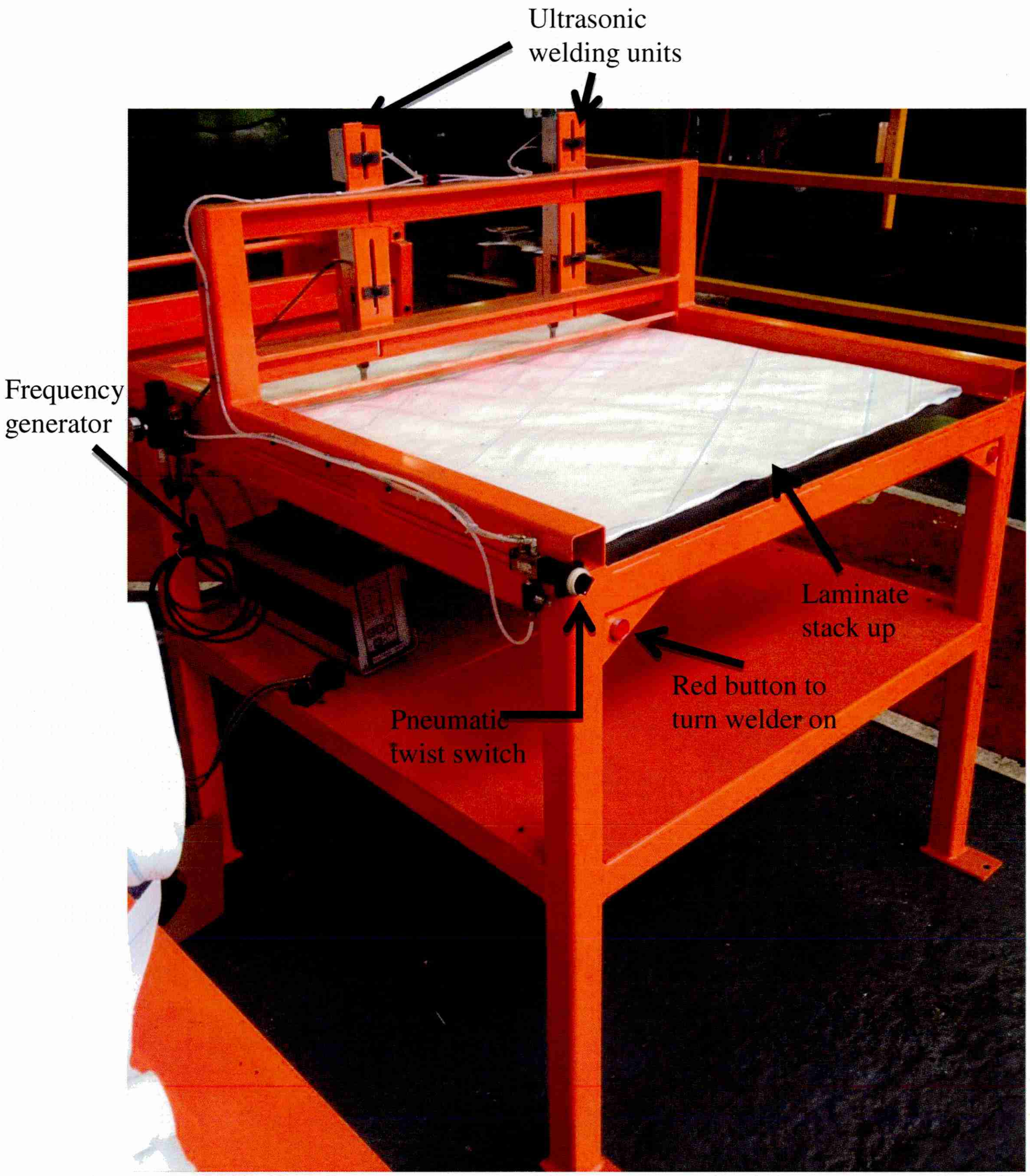


Figure 129: Stage 4 – Part Consolidation

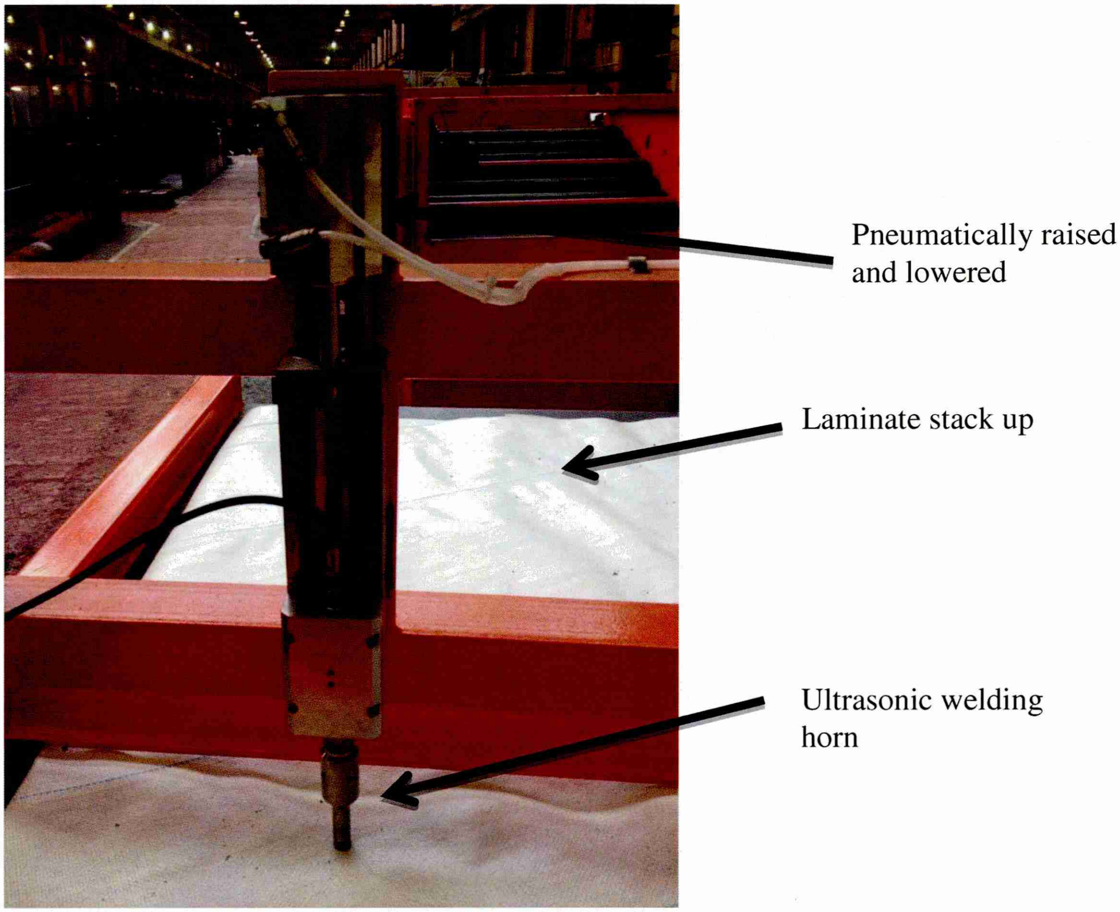


Figure 130: Stage 4 – Ultra Sonic Welding Unit

Stage 4 cost £14,480 to manufacture, compared to the estimated cost of £22,000 in chapter 5. This was achieved by using 2 ultrasonic welding heads instead of 4, but still achieving 4 welds on the material by rotating the material through 180 degrees. The ultrasonic welding heads cost £11,980 including the frequency generators, with the materials costing £1,000 and fabrication costing £1,500. This resulted in a saving on the estimated price of £7,520.

Chapter 10 – Discussion & Conclusions

Through this project the author has identified a gap in the market for the automation of off axis fibre reinforced thermoplastic laminates from in-line material, investigated the need for mass production in the automotive sector, and developed a solution to achieve the finished product at a rate of $1m^2$ of laminate every 20 seconds making this material available for mass production applications. The material was tested and it was determined that the characteristics of the component could be improved and the mass reduced by using a 5 ply thermoplastic laminate. This would increase the failure load of the component and reduce the mass by in excess of 50%. The reduced mass of the component results in a lighter vehicle with reduced fuel consumption and reduce carbon emissions as set out in the government directive.

From testing the author determined that with a 5 ply laminate with the orientation 90, 30, -30, 30, 90 a composite panel could be produced with high endurance properties which are comparable to steel components based upon static test data and from market research determined the widths of laminate and production rate required to make the project feasible.

Using this information the author designed and developed a prototype machine to automate the production of off axis fibre reinforced thermoplastics at commercially exploitable production rates. The machine consisted of 4 stages which;

- Takes rolls of the raw material 343mm wide and joins them using a hot air weld to form a wide material. This material is then cut to the correct with of 1010mm.
- The roll of material 1010mm wide is then processed around a mandrel to form a 2 ply tube of off axis fibre reinforced material, again using a hot air weld. This tube is then compressed to form a $1m^2$ 2 ply off axis material.
- The 1010mm wide roll of material can also be cut into linear lengths to produce a 1 ply inline laminate layer using a guillotine. These lengths are cut to 1m.
- The off axis 2 ply material and the inline lengths of material are combined into the desired laminate stack up of 90, 30, -30, 30, 90 and ultrasonically staked to form a part consolidated laminate.

10.1 Final Production Rates & Processing Costs:

The machine developed to achieve the mass production of the off axis sheets was conceptually designed and developed by the author and was manufactured by Joseph Rhodes Ltd. According to calculations and tests conducted by the author the machine operates at a production rate of $1m^2$ of 5 ply part consolidated material every 20 seconds, with the hot air welding machine on stage 2 running at 30m/min as opposed to the 40m/min achieved during initial trials. This production time is taking into account the transition of material between stage 1 to stage 2, stage 2 to stage 4 and also stage 1 to stage 3 as well as the staking of the material at stage 4. This production rate results in expected production volumes of;

3 sheets per minute x 60 minutes = 180 part consolidated sheets per hour

180 sheets per hour x 8 hours = 1,440 part consolidated sheets per day

1,440 sheets per day x 5 days = 7,200 part consolidated sheets per week

7,200 sheets per week x 4 weeks = 28,800 part consolidated sheets per month

28,800 sheets per month x 12 months = 345,600 part consolidated sheets per shift-year.

This volume is 123% of the volume required by Nissan to produce a panel on their Nissan Quashqui range. If Nissan operated a 3 shift working day this value could be tripled to achieve production volumes of up to 370% of that required by Nissan to produce a panel for a vehicle. This would allow Nissan to produce 3 panels for a given vehicle with a single production line, or the same panel for 3 different vehicles.

The actual expenditure on materials and capital equipment to produce the prototype machine was in excess of £154,000 (excluding labour) compared to £192,000 (also materials and capital equipment) estimated in the chapter 5 – concept stage.

The cost to produce a part consolidated component as a result of the actual production rate and the machine build cost is;

The raw material cost of a 5 ply m^2 laminate = £12.68

Machine build costs of £154,729 + labour and overheads estimated at £120,000* = £274,729

Depreciation over 5 years = £54,946/year

Finance at 6% of £274,729= £16,484/year

Running costs at 5% = £13,736/year

Labour costs of operating the machine at £20,000/year

Total annual cost = (£54,946 + £16,484 + £13,736+ £20,000) = £105,166/year

Processing cost per component = £105,166 / 345,600 = 30.4p (31p) for single shift operation

Total production cost of 5 ply laminate = £12.68 + £0.31 = £12.99

For 3 shift operation this would be:

(£54,946 + £16,484 + £13,736+ £60,000) = £145,166/(3 x 345,600) = 14p/component with a total production cost of £12.68 + 14p = £12.72 for 3 shift operation.

*Labour and overheads rates based on an average of £30/hour, and a total labour resource of 4000 man hours being required to produce this machine consisting of:

Table 20: Estimated Man Hours Per Task

Man Hours	Task
2000	Designing
1200	Machining
230	Fabricating
110	Painting
460	Fitting

10.2 Conclusions:

The project achieved its objectives which were;

- To develop lightweight material to replace steel in automotive applications with significant mass savings.
- To build a prototype machine to automate the process of producing off axis fibre reinforced thermoplastic materials at commercially exploitable mass production rates.
- And maintain low machine processing costs.

In doing so a new material has been made available to mass production automotive manufacturers which has very real benefits of reduced vehicle mass, increased recyclability reduced fuel consumption and reduced carbon emissions. Although the production rates achieved in the feasibility study have not been achieved, production volumes 123% of that required by Nissan could still be achieved in an 8 hour production day, with the potential to reach 370% production volumes given a 3 shift working day. With a machine cost of £274,729 compared to the millions of pounds spent on steel presses for steel automotive panels, or the multi millions spent on carbon fibre processing equipment, this manufacturing process is highly desirable.

Part of this project was presented at the Automated Composites Manufacturing Symposium held at Concordia University, Montreal in March 2013. The presentation highlighted the fact that a method had been devised to produce fibre reinforced thermoplastics automatically at commercially exploitable production rates, as well as highlighting the increased failure loads compared to the steel components currently used. A copy of the presentation can be found in appendix 4.

The author applied for and was awarded a £192,000 government funded SMART grant to help fund the machine build. With this grant Joseph Rhodes Ltd was able to manufacture the prototype machine.

In addition to this the author also submitted a patent application through Appleyardlees, 6th Floor, 1 East Parade, Leeds, West Yorkshire LS1 2AD to protect the design of both concept 1 and concept 2 of the machine, so the company could exploit both concepts depending on the requirements of the customer. The patent application along with the patent drawings can be found in appendix 5.

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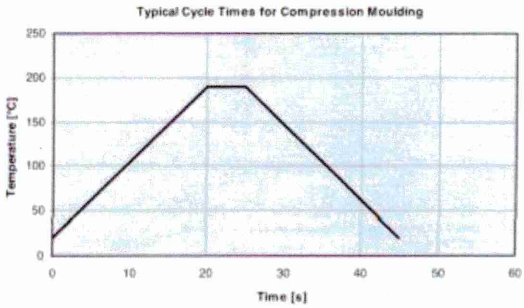
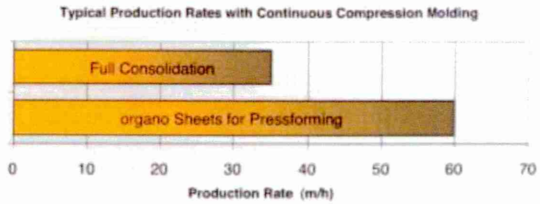
Appendix 1 – Plytron Data Sheet:

elekon





Typical Properties of Plytron® GN 638 T

Fibre Glass Content & Tape Nominal Dimensions			
Glass content	wt-%	60	
	vol-%	35	
Ply thickness	mm	0.27	
Tape width	mm	300	other widths on request

Property of Plates made with Plytron® (ca. 3 mm thickness)		**Unit**	**0°**	**[-45,0,45,90]s**	**[(0,90)2]s**
Density		g/cm³	1.5	1.5	1.5
Tensile	strength	MPa	720 [1] 11 [2]	178	360
	modulus (E_{11})	GPa	28 [1]	11	16
	modulus (E_{22}), calculated	GPa	3.72 [2]		
	strain to break	%	1.9	2.4	2.5
Flexural	strength	MPa	436 [1]	229 [3] 110 [4]	300 [1] 254 [2]
	modulus	GPa	21 [1]	8.4 [3] 3 [4]	16.8 [1] 8.4 [2]
Shear	strength - Isopescu	MPa	19 [1]		
	modulus G_{12}	GPa	1.39		
	Poisson's ratio (v_{12}), calculated	-	0.38		
ILSS	DIN 65148	MPa	18 – 22		
	Strain to break	%	0.77		
Compression	strength (Boeing)	MPa	366		
Fracture toughness (G_{12})		kJ/m²	0.94		
Impact	Izod (notched) @ 23°C	J/m²	383		
	@ -30°C	J/m²	425		
Temperature	Melting T_m ISO 3146	°C	165		
	Glass Transition Tg	°C	-15		
HDT- Heat Deflection Temperature	@ 1.80 MPa (A)	°C	156		
	@ 0.45 MPa (B)	°C	164		
Softening point	Vicat B, 49.05 N		134		
Flammability	UL 94 Rating, < 3 mm		HB		
Oxygen Index	ISO 4589	%		19.5	
Thermal expansion coefficient		10^{-6}/K	7 [1] 90 [2]	20 [3] 20 [4]	20 [1] 20 [3]

[1] parallel or [2] transverse to fibre orientation [3] 0° layers are 2nd ply inward from surface [4] 0° layers are 3th ply inward from surface

The technical information listed is for guidance purpose only.

Appendix 2 – Celstran Data Sheet:

PRELIMINARY DATA

Celstran® CFR-TP PP GF70-13

Ticona

Performance Driven Solutions™

General Description: Celstran® CFR-TP PP GF70-13 is a 70% E-glass by weight PP (polypropylene) continuous fiber (uni-directional) reinforced thermoplastic composite tape. This material exhibits a high strength-to-weight ratio, excellent toughness and chemical resistance. It is well suited for industrial, automotive and sporting goods applications where cost and process ability are critical. The material is available in natural and black colors.

	Property	Value	Unit	Value	Unit
MATERIAL	**Polymer**	PP			
	Fiber Type	E-glass			
	Density	0.060	lb/in³	1.67	g/cm³
	Fiber Content	70	% by wt.		
	Fiber Volume	44	% by vol.		
	Tape Thickness**	0.0103	in	0.26	mm
	Tape Width (max.)*	12	in	305	mm
	Tape Areal Weight**	12.8	oz/yd²	435	g/m²
	Fiber Areal Weight**	9.0	oz/yd²	305	g/m²

*Custom tape widths may be available. Slit tapes are available down to 0.25 in (6mm).

**Nominal value shown, actual value may vary.

	Property[1]	Value	Unit	Value	Unit	Test Method
MECHANICAL	**Tensile Strength**	130	ksi	910	MPa	D3039
	Tensile Modulus	4.9	Msi	34.0	GPa	D3039
	Elongation at Break	2.90	%	2.90	%	D3039
	Flexural Strength	102	ksi	730	MPa	D790
	Flexural Modulus	5.1	Msi	31.5	GPa	D790

[1]Orientation 0°

	Property	Value	Unit	Value	Unit
THERMAL	**Melt Temperature**	343	°F	173	°C
	Glass Transition Temperature	14	°F	-10	°C

Contact Information

Americas
Ticona Engineering Polymers
Product Information Service
8040 Dixie Highway
Florence, KY 41042
USA
Tel.: +1-800-833-4882
Tel.: +1-859-372-3244

Customer Service
Tel.: +1-800-526-4960
Tel.: +1-859-372-3214
Fax: +1-859-372-3125
email: prodinfo@ticona.com

Europe
Ticona GmbH
Information Service
Am Unisyspark 1
65843 Sulzbach, Germany
Tel.: +49 (0)180-584 2662 (Germany)*
+49 (0)69-305 16299 (Europe)**
Fax: +49 (0)180-202 1202

See example below for rate information:
* 0.14 €/min + local landline rates
**0.06 €/call + local landline rates

email: infoservice@ticona.de

Ticona on the web: www.ticona.com

Asia
Celanese (China) Holding Co., Ltd.
4560 Jinke Road
Shanghai 201210
P.R. China

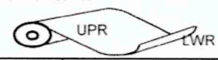
Customer Service
Tel.: +86-21-3861 9288
Fax: +86-21-3861 9588
email: infohelp@ticona.com

Celanese

Ticona – A Business of Celanese

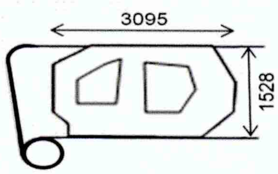
Appendix 3 - Nissan Panel Spec Sheets:

NMUK STEEL SPECIFICATIONS				Issue:	D
Model:	PL	Ref. No.	PL006	Date:	24-Aug-09
Part Name:	BODY SIDE OTR RH				
Panel No. (s):	76022 JD000				
Coil No.:	76022 JD0BC			FULL FINISH SIDE	
Blank No.:	76022 JD0DB			Full finish to : Upper	
Application	ALL				
Material Spec.	Coil Dimensions (mm)				

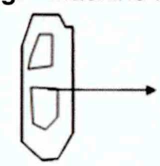


GZES	Thickness Coated	Thickness Uncoated	Width		Pitch	
Material Coating:						
GI	0.77	0.75	1528		3095	
Mechanical Prop`s	YS	TS	EL (80mm)	n (90)	r (90)	BH
(Trans) (N/mm2)	Refer to NES or NEM standards for detailed information					
Blank Weight (Kg)	28.62		Panel Weight (Kg)		11.6	

Blanking Method: Machine flow ----->



Panel Forming: Machine flow ------>



PREVIOUS ISSUE

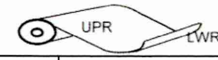
Reason For This Issue:	Changes From Previous Issue:
Grade down from GZSES to GZES	grade coil and blank numbers updated

Comments		Specification Status
Coil ID:	610mm	ADOPTED
Oil Coating:	1.5g/m2	
Slit:	NO	
Method:	N/A	
Coil Width Tol`:	-0mm / +5mm	
Coating per Side:	10µ	
Other:		

SIGN OFF

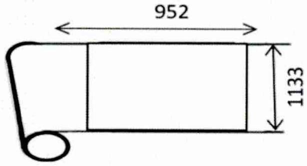
Department	Engineering			Prod`n	Prod`n Cont	Purch
Sign Level	Eng	Snr Mgr	Mgr	Sup`r	Cont	Snr Cont
Signature & Date						

NMUK STEEL SPECIFICATIONS				Issue:	C
Model:	PL	**Ref. No.**	PL034	**Date:**	06-Nov-08
Part Name:	**FLOOR RR RR**				
Panel No. (s):	74514 JD00A				
Coil No.:	74514 JD00C			**FULL FINISH SIDE**	
Blank No.:	74514 JD00B			Full finish to :	Upper
Application	ALL				

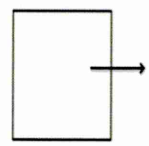


Material Spec.	Coil Dimensions (mm)					
GXES	Thickness Coated	Thickness Uncoated	Width		Pitch	
Material Coating:						
GI	0.67	0.65	1133		952	
Mechanical Prop`s	YS	TS	EL (80mm)	n (90)	r (90)	BH
(Trans) (N/mm2)	Refer to NES or NEM standards for detailed information					
Blank Weight (Kg)	5.67		**Panel Weight (Kg)**		4.37	

Blanking Method: Machine flow ----->



Panel Forming: Machine flow ------>



PREVIOUS ISSUE

Reason For This Issue:	**Changes From Previous Issue:**
2mm width reduction	blank width chnaged

Comments		**Specification Status**
Coil ID:	610mm	ADOPTED
Oil Coating:	1.5g/m2	
Slit:	NO	
Method:	N/A	
Coil Width Tol`:	-0mm / +5mm	
Coating per Side:	10µ	
Other:		

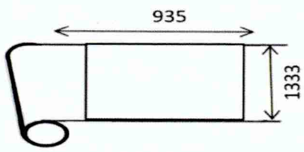
SIGN OFF

Department	**Engineering**			**Prod`n**	**Prod`n Cont**	**Purch**
Sign Level	**Eng**	**Snr Mgr**	**Mgr**	**Sup`r**	**Cont**	**Snr Cont**
Signature & Date						

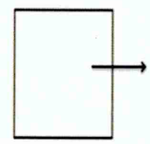
NMUK STEEL SPECIFICATIONS					Issue:	E
Model:		PL	Ref. No.	PL018	Date:	30-Apr-09
Part Name:	GLASS ROOF					
Panel No. (s):	73112 JD010					
Coil No.:	73112 JD1CC				FULL FINISH SIDE	
Blank No.:	73112 JD1DB				Full finish to :	Upper
Application	ALL					
Material Spec.	Coil Dimensions (mm)					

ZES	Thickness Coated	Thickness Uncoated	Width		Pitch	
Material Coating:						
NONCOATED		0.7	1133		935	
Mechanical Prop`s	YS	TS	EL (80mm)	n (90)	r (90)	BH
(Trans) (N/mm2)	Refer to NES or NEM standards for detailed information					
Blank Weight (Kg)	6.85		**Panel Weight (Kg)**		4.53	

Blanking Method: Machine flow ----->



Panel Forming: Machine flow ------>



PREVIOUS ISSUE

Reason For This Issue:	Changes From Previous Issue:
supplier changed	coil and blank numbers

Comments		Specification Status
Coil ID:	610mm	ADOPTED
Oil Coating:	1.5g/m2	
Slit:	NO	
Method:	N/A	
Coil Width Tol`:	-0mm / +5mm	
Coating per Side:	10µ	
Other:		

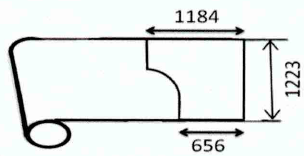
SIGN OFF

Department	Engineering			Prod`n	Prod`n Cont	Purch
Sign Level	Eng	Snr Mgr	Mgr	Sup`r	Cont	Snr Cont
Signature & Date						

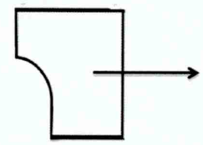
NMUK STEEL SPECIFICATIONS				Issue:	B
Model:	X32L	Ref. No.	XL001	Date:	29-Jul-09
Part Name:	BODY SIDE OTR RH				
Panel No. (s):	63112 BR00A				
Coil No.:	63112 BR00C			FULL FINISH SIDE	
Blank No.:	63112 BR00B			Full finish to : Upper	
Application	ALL				
Material Spec.	Coil Dimensions (mm)				

Material Spec.	Thickness Coated	Thickness Uncoated	Width		Pitch	
GZE220BH						
Material Coating:						
GI	0.72	0.7	1223		1842	
Mechanical Prop`s	YS	TS	EL (80mm)	n (90)	r (90)	BH
(Trans) (N/mm2)	Refer to NES or NEM standards for detailed information					
Blank Weight (Kg)	6.37		Panel Weight (Kg)		2.6	

Blanking Method: Machine flow ----->



Panel Forming: Machine flow ------>



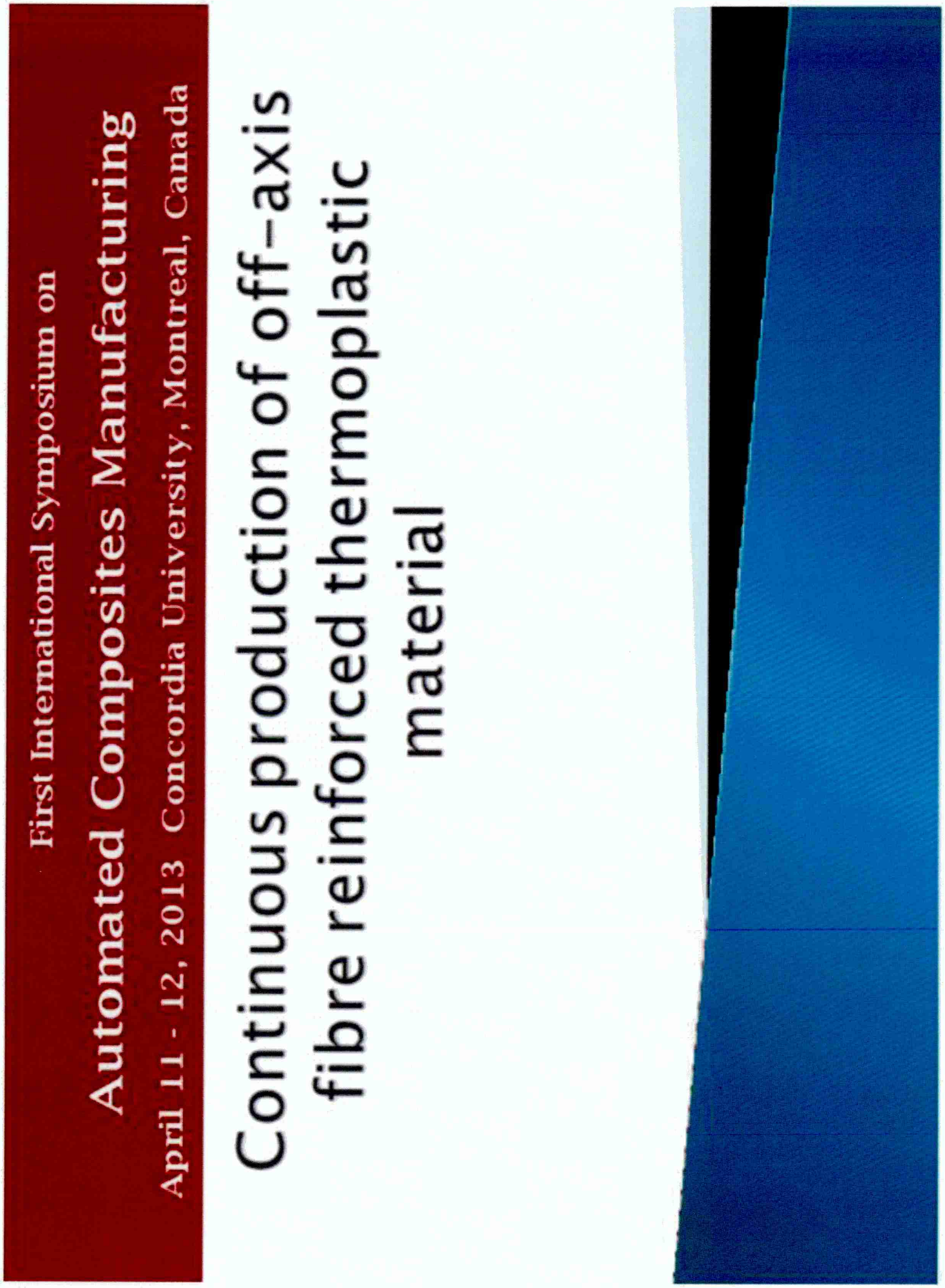
PREVIOUS ISSUE

Reason For This Issue:	Changes From Previous Issue:
X32L ADDED	Application changed

Comments		Specification Status
Coil ID:	610mm	ADOPTED
Oil Coating:	1.5g/m2	
Slit:	NO	
Method:	N/A	
Coil Width Tol`:	-0mm / +5mm	
Coating per Side:	10µ	
Other:		

SIGN OFF

Department	Engineering			Prod`n	Prod`n Cont	Purch
Sign Level	Eng	Snr Mgr	Mgr	Sup`r	Cont	Snr Cont
Signature & Date						


First International Symposium on
Automated Composites Manufacturing
April 11 - 12, 2013 Concordia University, Montreal, Canada
Continuous production of off–axis fibre reinforced thermoplastic material

GROUP RHODES

Knowledge Transfer Partnerships

Technology Strategy Board
Driving Innovation

Sheffield Hallam University
SHARPENS YOUR THINKING

submitted by:

Professor Graham Cockerham,
Dr Syed Hasan,
Sheffield Hallam University, UK
Philip McDonald , Barry Richardson,
Joseph Rhodes Ltd, Wakefield, UK

KTP Programme 008385 [ref1]

Introduction

This presentation outlines the results, 21months into a 30 month Knowledge Transfer Partnership between J Rhodes Ltd of Wakefield and Sheffield Hallam University aimed at

'Developing equipment for the continuous production of semi-finished, recyclable off-axis, fibre reinforced thermoplastic composite sheet materials, suitable for high impact structural use'

involving the appointment of a graduate with support from University and company staff.

Support– the authors gratefully acknowledge the following;

- KTP grant £64,875 to partially fund 30 month programme
- Smart Award £184,485 to build prototype machine

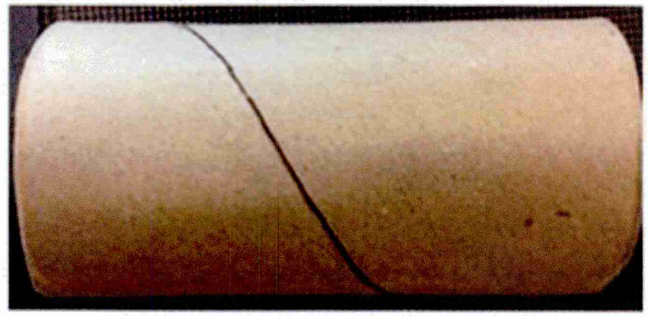
Introduction

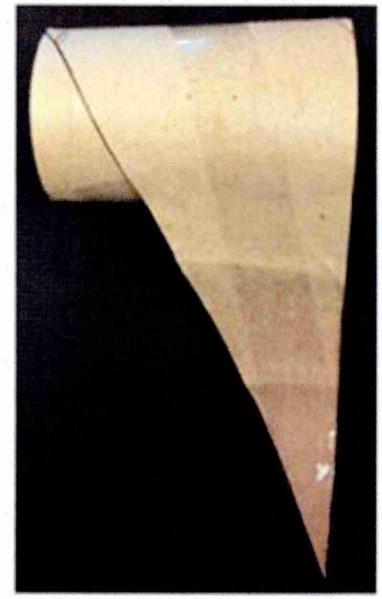
- Current manufacturing methods in automotive:
  - Resin transfer moulding
  - Manual lay up
  - Sheet moulding compound

- Processes are
  - Slow
  - Messy
  - Subject to excessive waste material
  - Labour intensive
  - Require large capital equipment.

- Solution – Automation on a mass production scale.

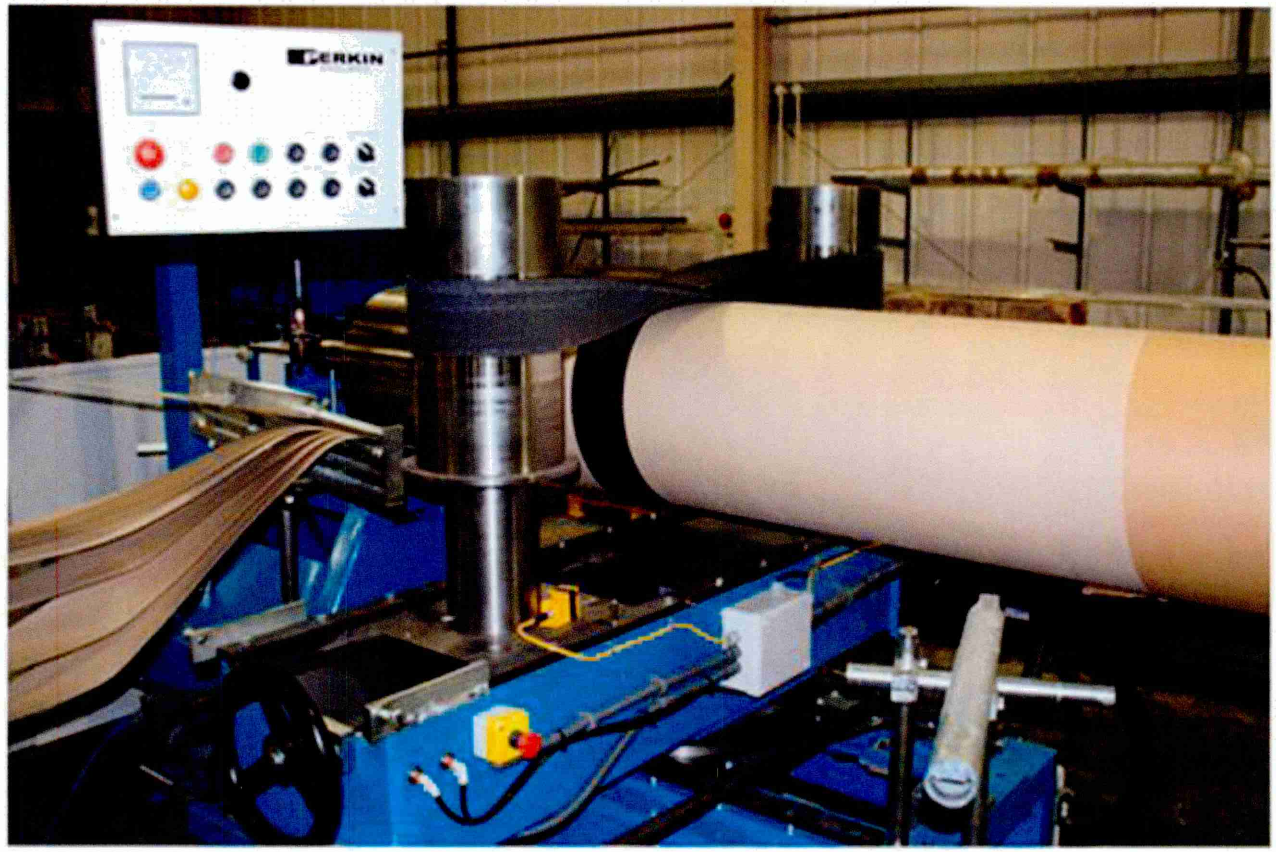
Idea Origins



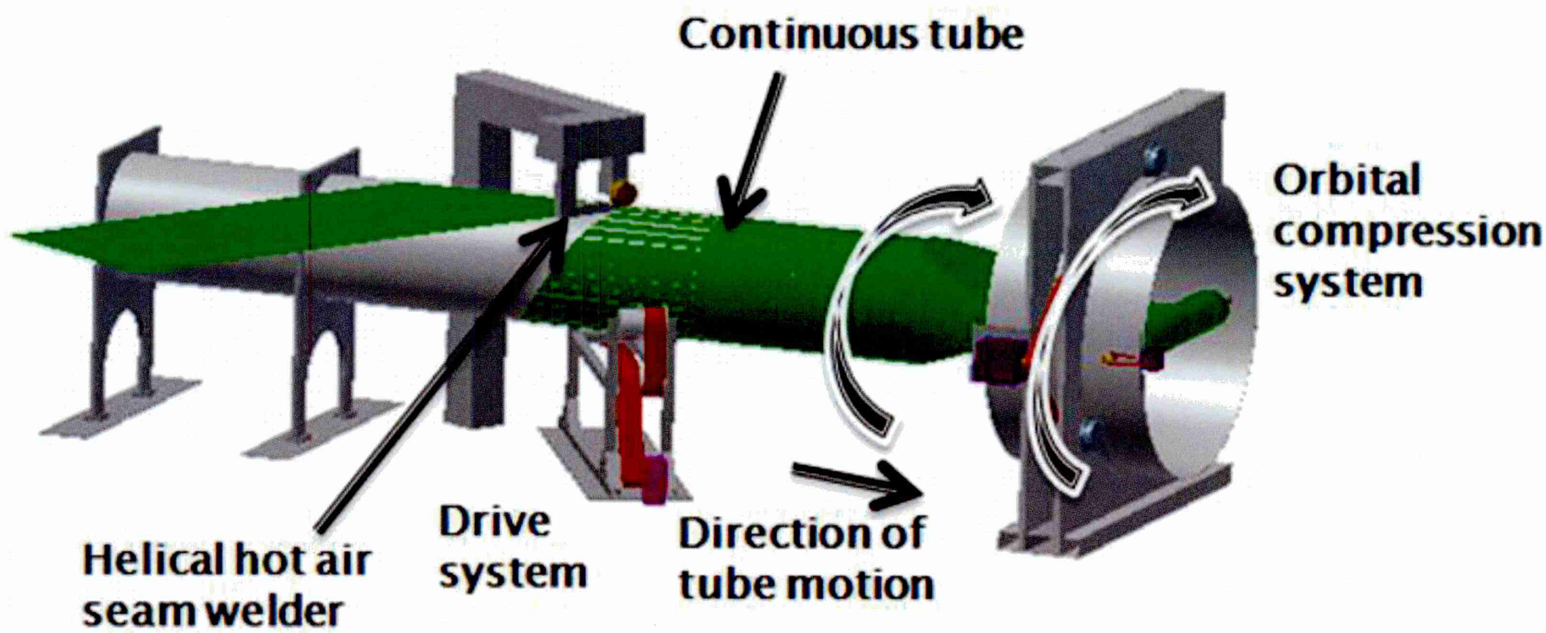


A continuous tube created from fibre reinforced tape using a helical hot-air weld based upon spiral winding of cardboard tubes

Paper Tube Making (ref 2)



Concept

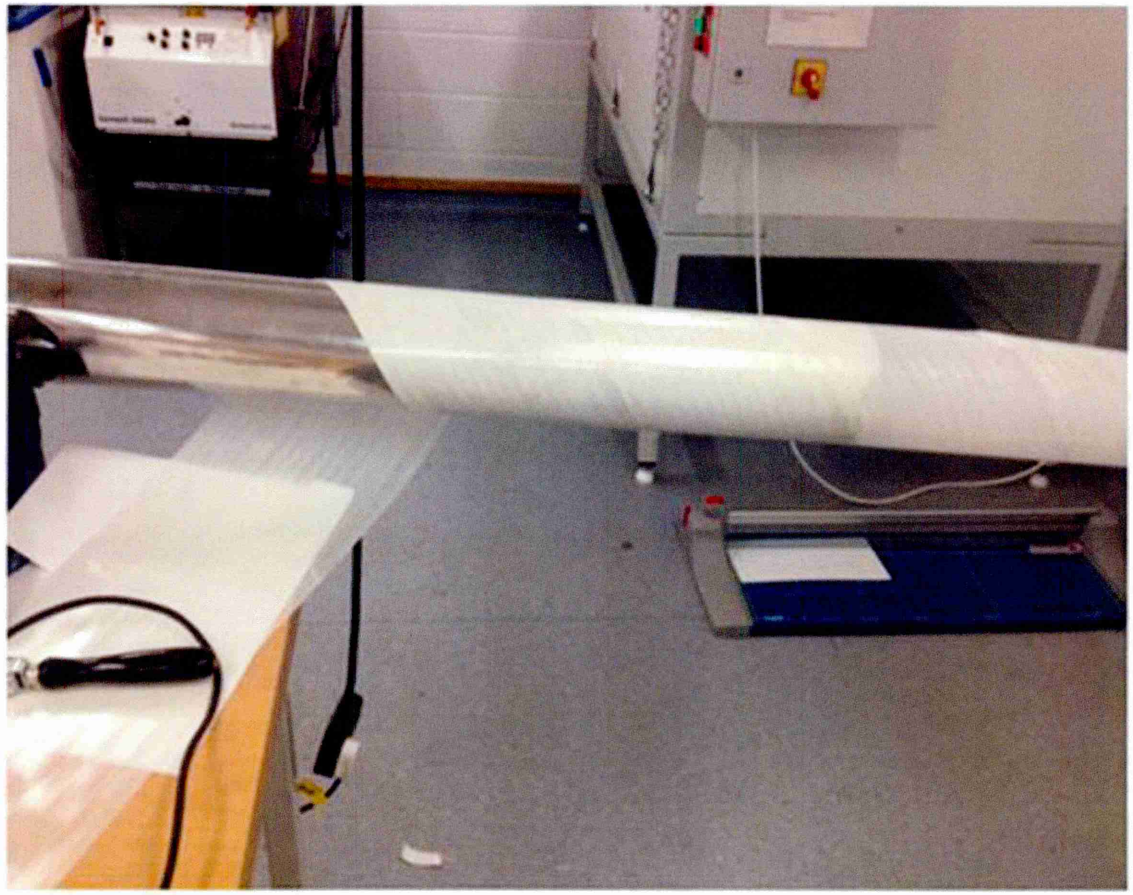


(UK Patent Application 1302511.9)

Proof of principle

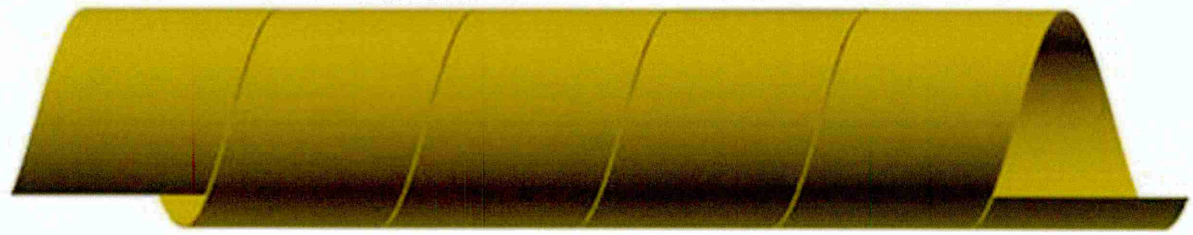
Manual trials have proven the helical weld can form a tube.

Proof of principle–tube forming



Proof of principle–compressing

Theory



Laminate width,

$W_L = W_T /(2\sin A_S)$

$W_L / W_T = 1/(2\sin A_S)$

Mandrel diameter,

$D_M = W_L /1.57$

$= W_T /1.57(2\sin A_S)$

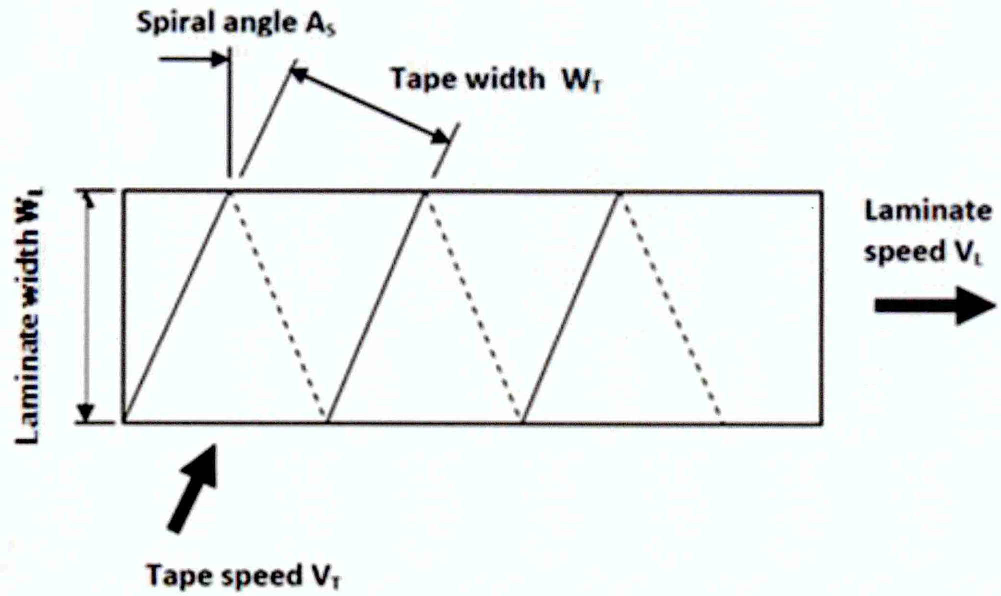
$0.5V_T W_T = V_L W_L =$

$V_L W_T /(2\sin A_S)$

$V_T /V_L = 1/(\sin A_S)$

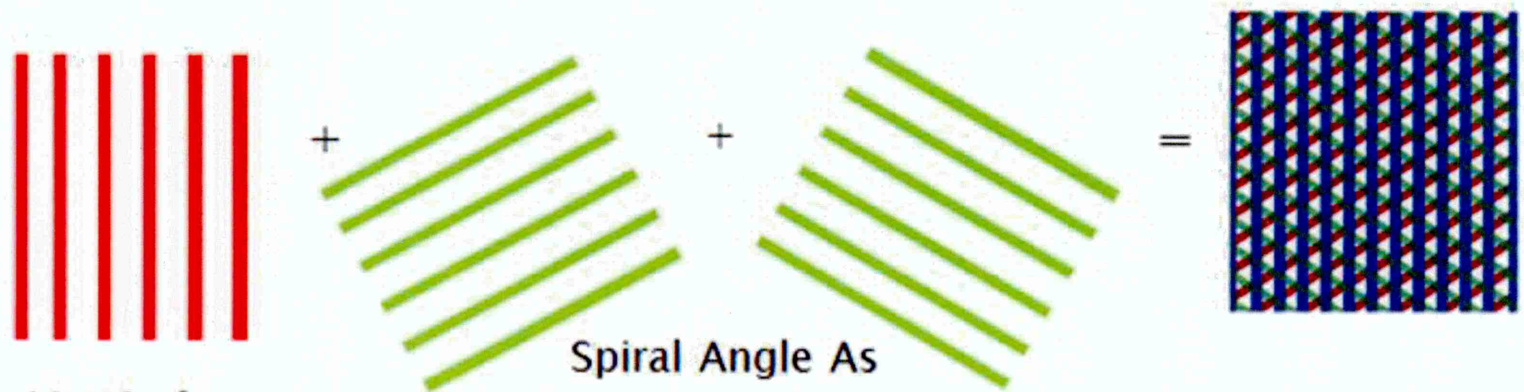
Production rate =

$0.5W_T V_T$ m^2/min



Semi-finished laminate

Example shows an axi-symmetric anisotropic laminate



Vertical

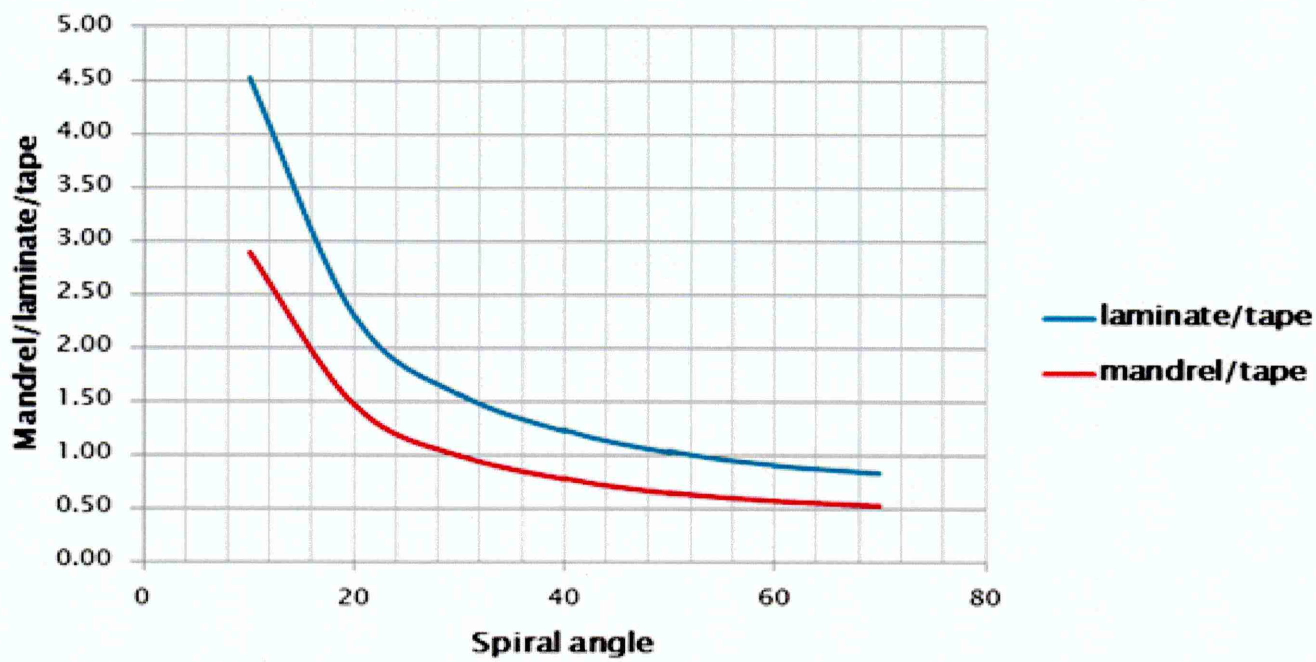
Tensile Load + 2 tensile load (sin 30) = 2 tensile load

Horizontal

Zero + 2 tensile load (cos 30) = 1.732 tensile load

Off axis production

Laminate/tape width as a function of spiral angle

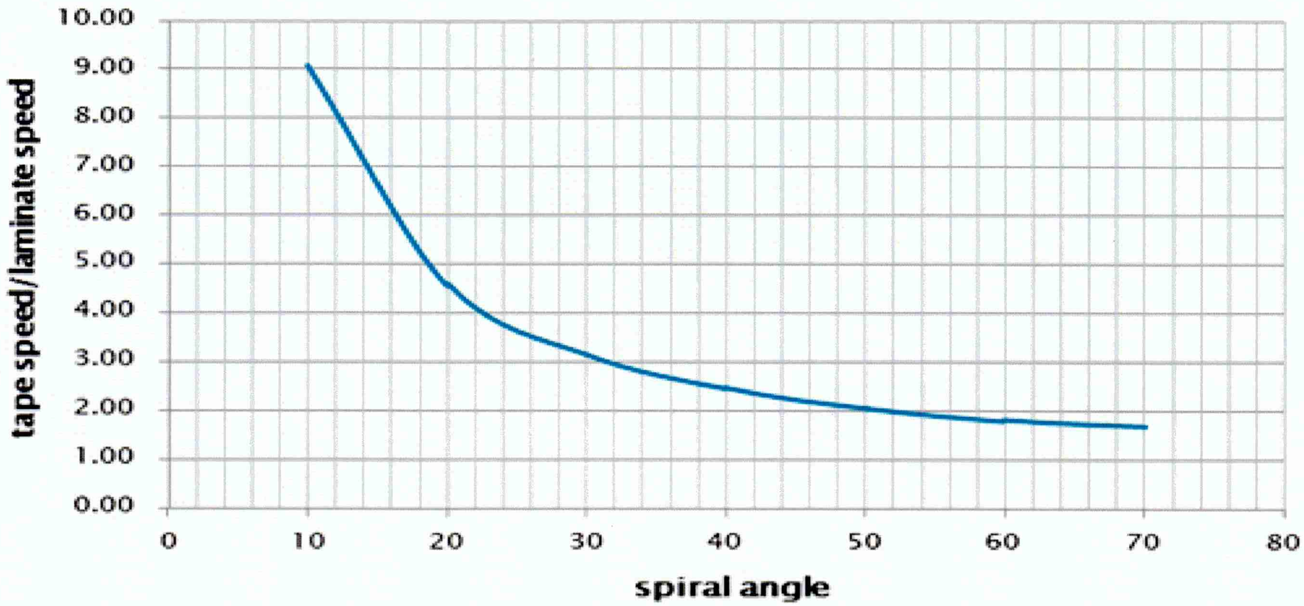


$W_L / W_T = 1.57 / (2 \sin A_S)$; $D_M / W_T = (2 \sin A_S)$

For tape of 350mm, angle of 30° , mandrel diameter= 350mm, laminate width <550mm

Off axis production

Tape (welding) speed / Laminate output speed as a function of spiral angle

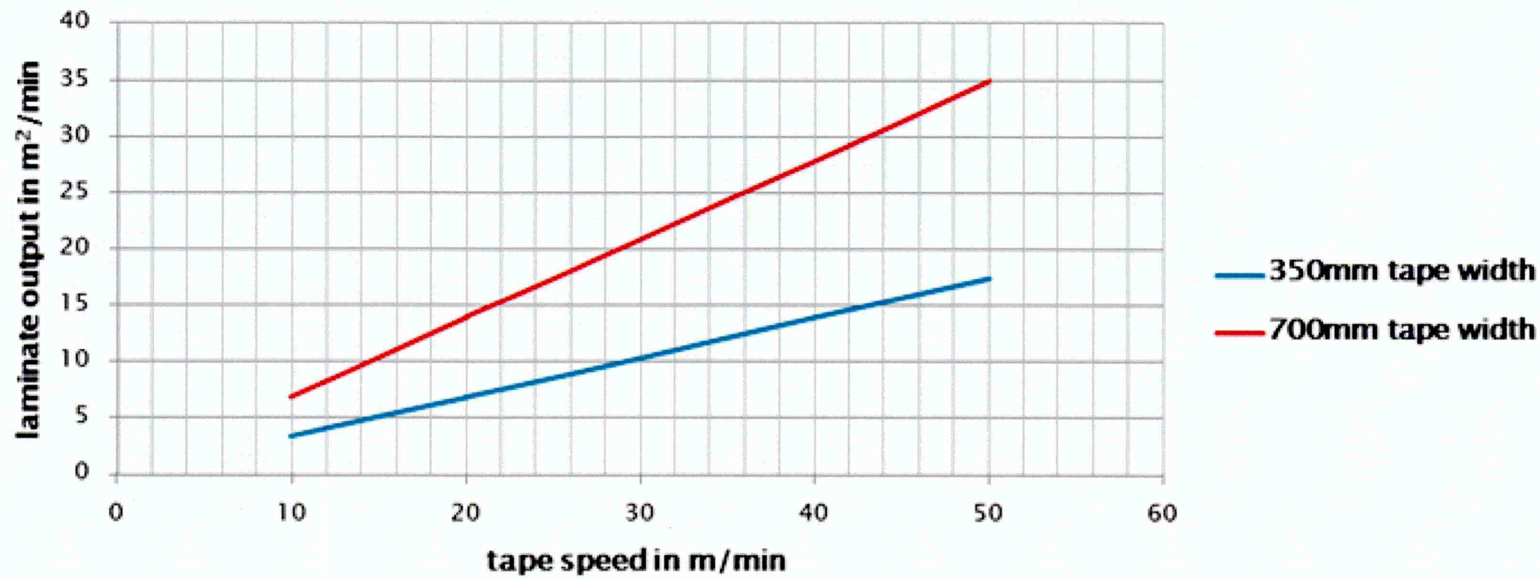


$V_T / V_L = 1.57/(\sin A_S)$

For tape welding speed of 40m/min, laminate output speed = 12.73 m/min

Off axis production

Laminate output rate as a function of tape width and speed



$$0.5W_TV_T = 0.35 \times 40 = 7 \ m^2/min$$

Commercial Feasibility

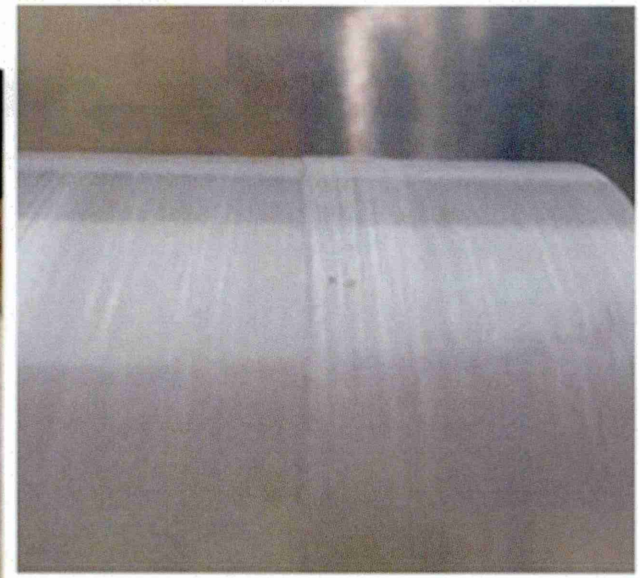
For tape speed of 40m/min and tape width of 350mm, laminate width=550mm, output speed = 12.73m/min = 5 sec/m sheet

For 24 hr/day , 7 days/week, 50 weeks/year operation, total linear production of 2 ply laminate = 6.4 million metres.

For 24 hr/day , 7 days/week, 50 weeks/year operation, total linear production of 2 ply laminate = 6.4 million metres.

Hot Air Weld

40 m/min weld speed achieved with 3.6kW power capacity machine



Steel Substitution

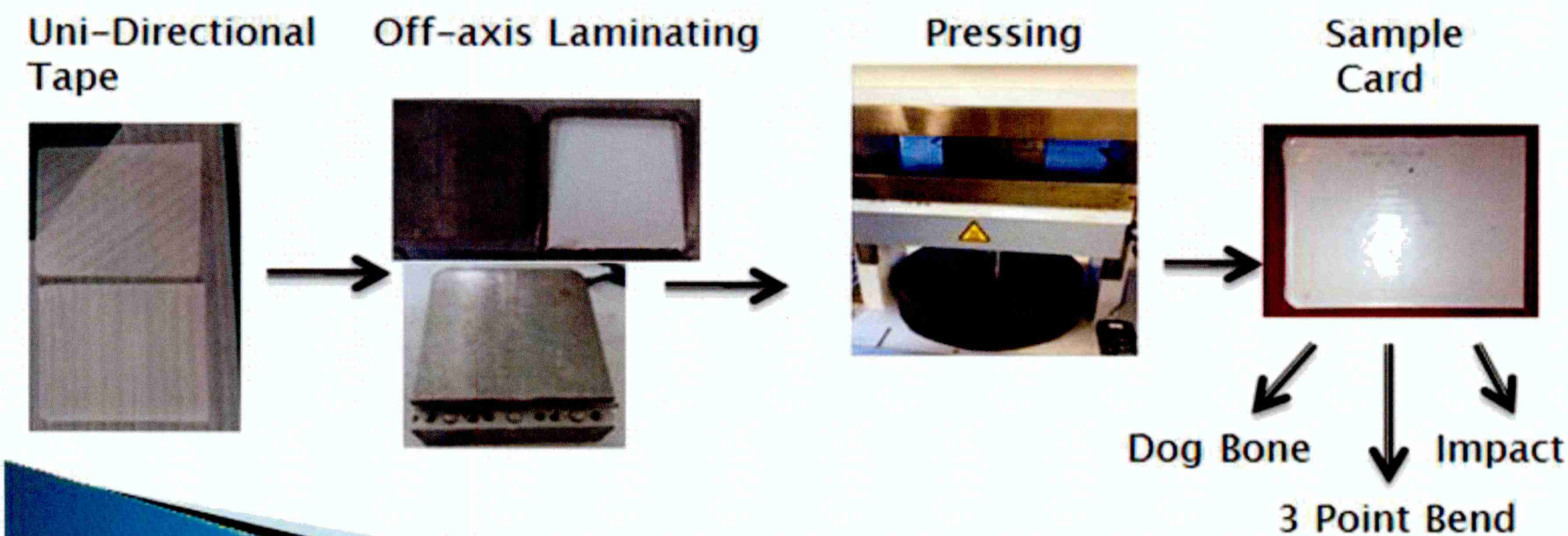
Using Ashby's Performance Index approach[ref4]
For plates and beams, load limit = $K_1 \sigma_y t^2$
and deflection $= K_2 / Et^3$
where σ_y = yield stress, E = Young's Modulus and t = component thickness

Hence for steel substitution $(\sigma_y t^2)_{sub} > (\sigma_y t^2)_{steel}$
so $(\sigma_y)_{sub} (t^2)_{sub} > (\sigma_y)_{steel} (t^2)_{steel}$
and $(t^2)_{sub} > (t^2)_{steel} (\sigma_y)_{steel} / (\sigma_y)_{sub}$

Also $(1 / Et^3)_{sub} < (1 / Et^3)_{steel}$
and $(t^3)_{sub} > (t^3)_{steel} E_{steel} / E_{sub}$

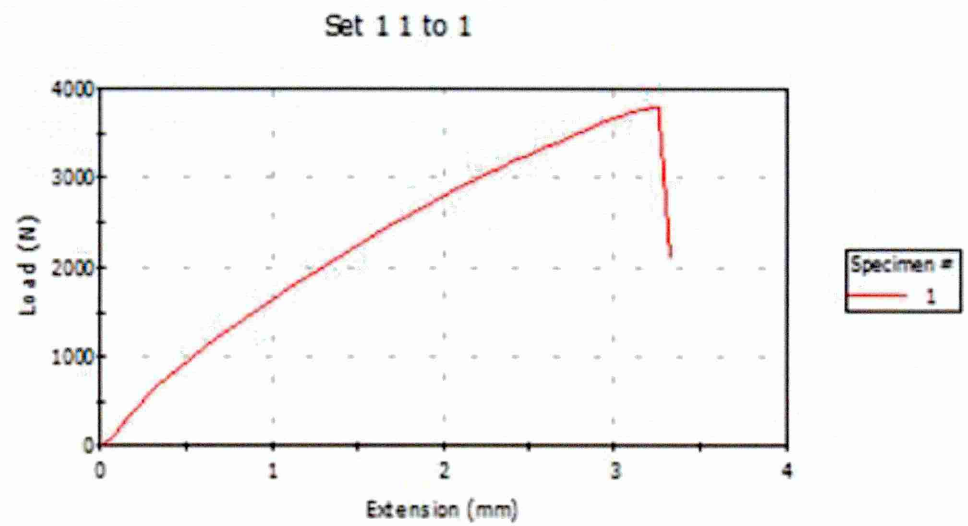
Material Testing

Extensive testing was conducted on various laminate combinations of spiral angle and ply numbers to find the optimum configuration.

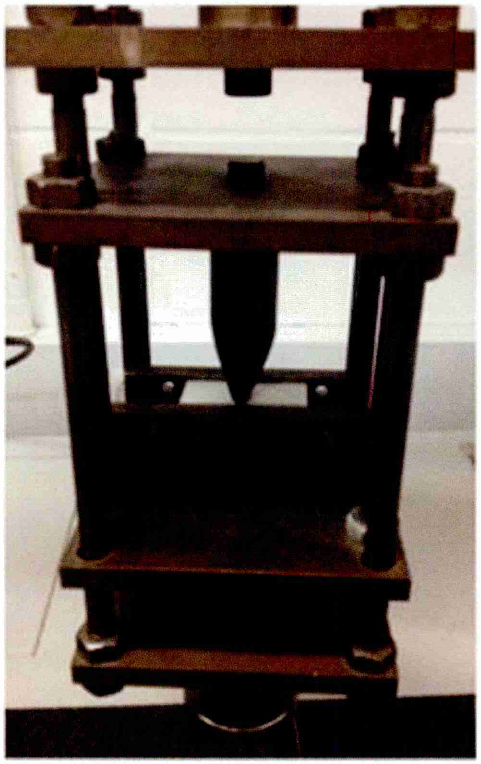


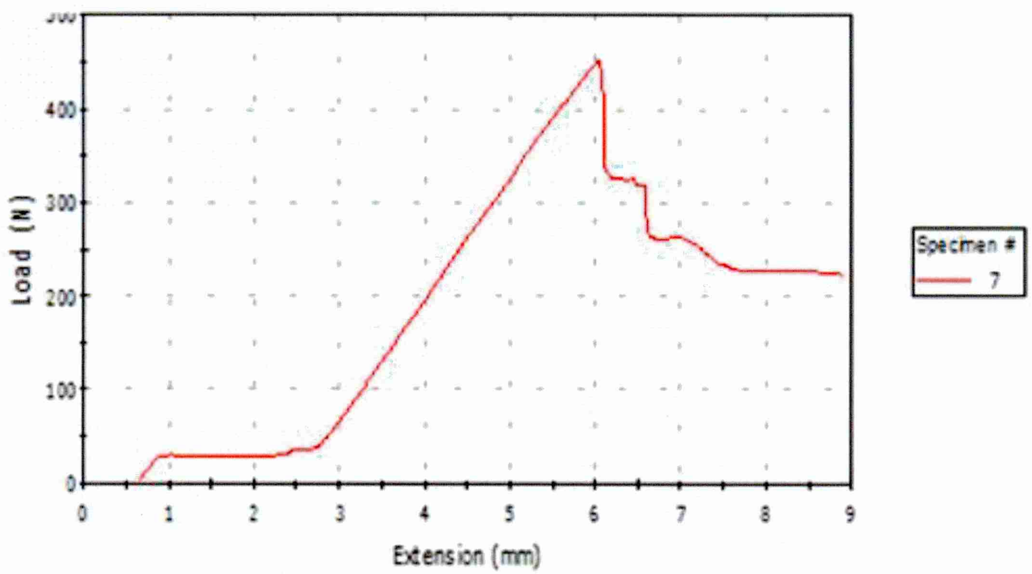
Tensile Testing

Tape Breaking Load and Modulus determined



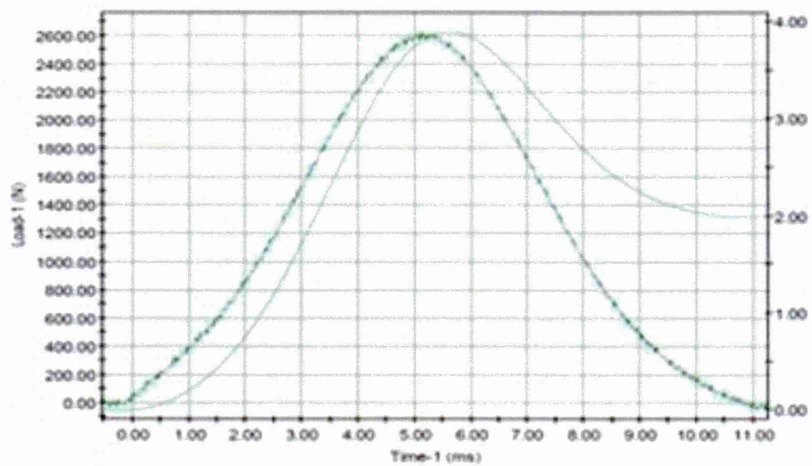
3 Point Bending



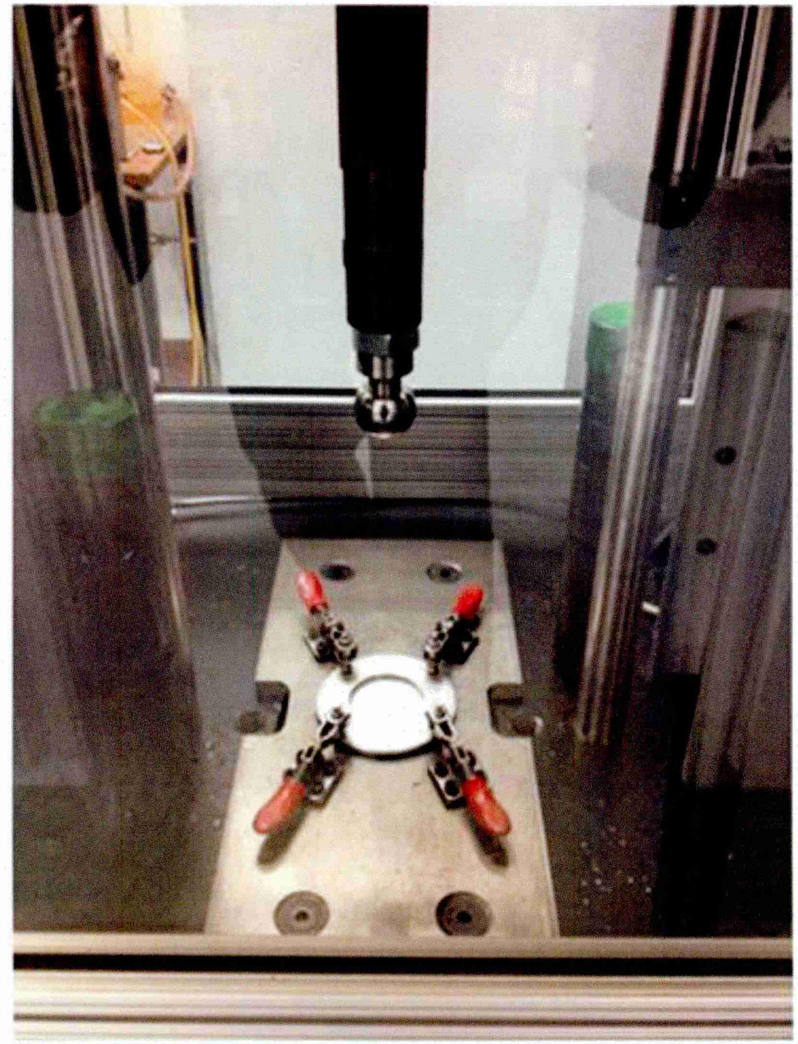


Bending load limit determined

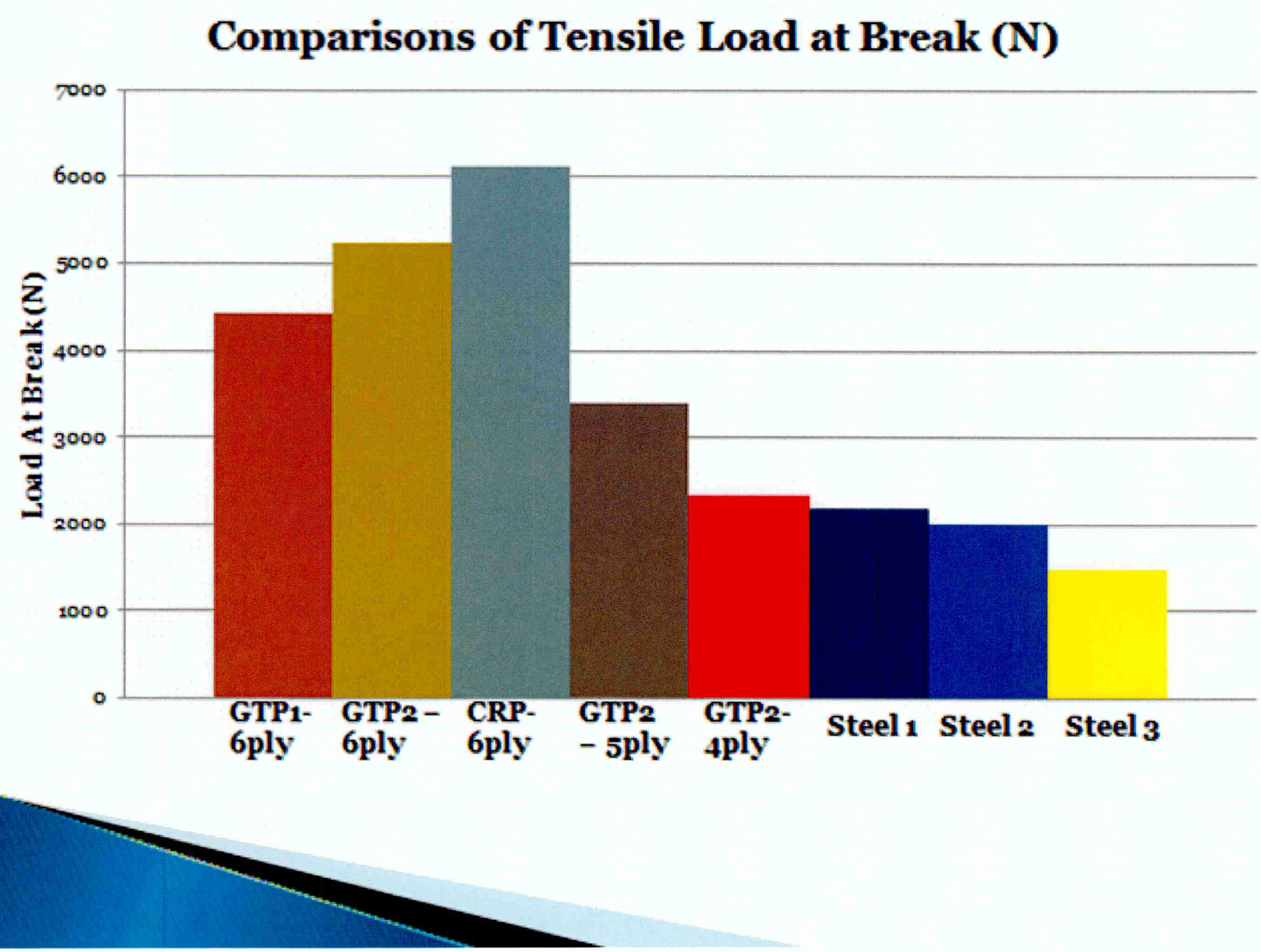
Impact Testing



Impact load and energy absorbed determined

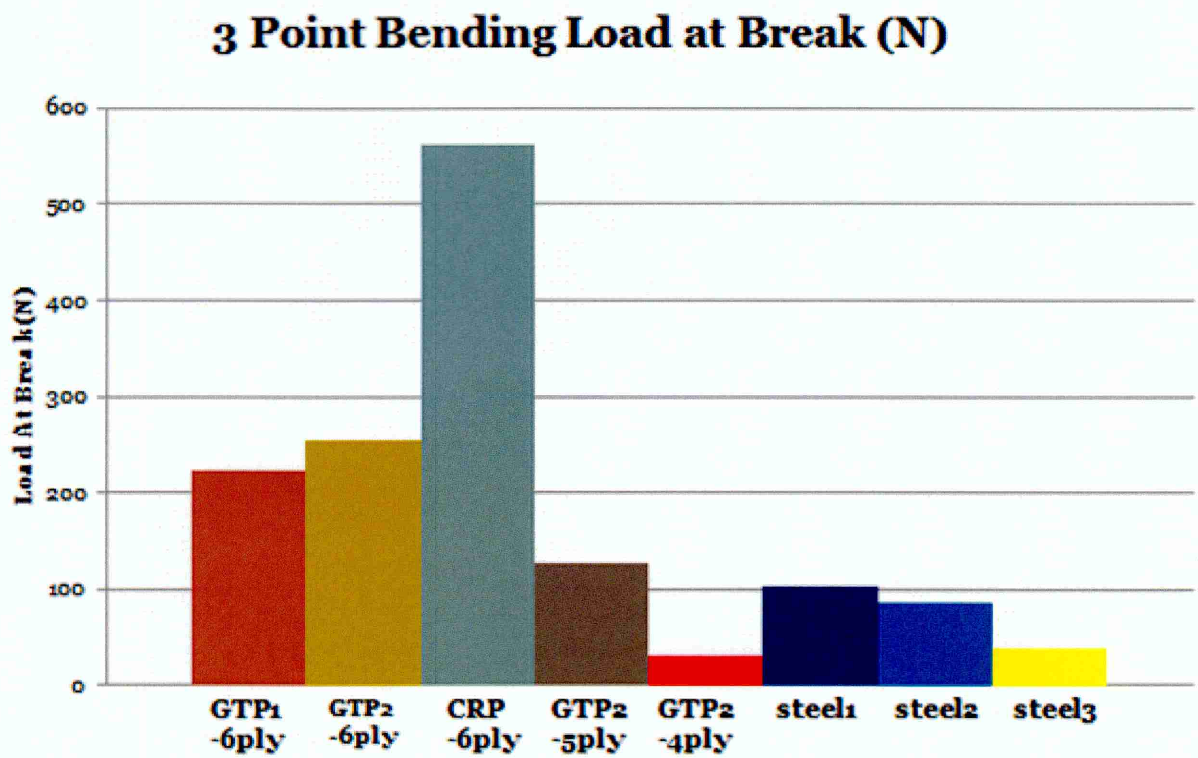


Results



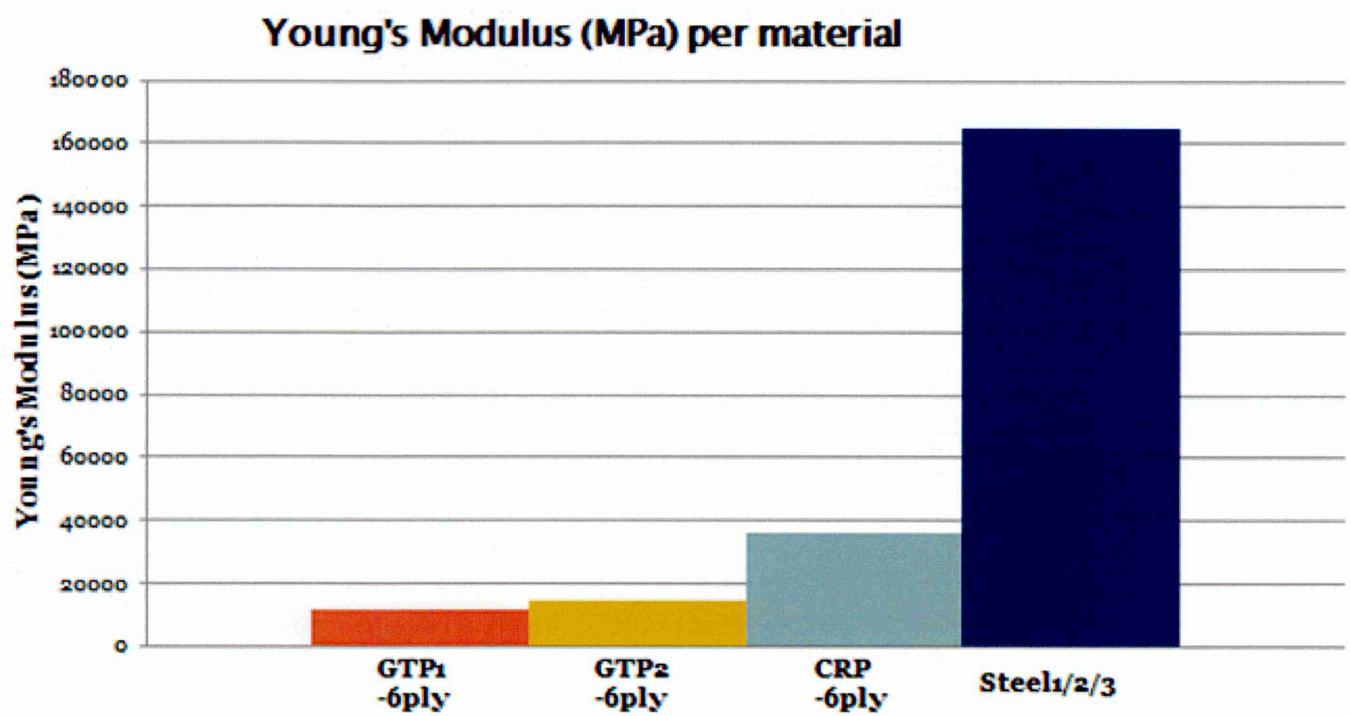
Comparisons of Tensile Load at Break (N)
Load At Break (N)
7000
6000
5000
4000
3000
2000
1000
0
GTP1-6ply
GTP2 – 6ply
CRP-6ply
GTP2 – 5ply
GTP2-4ply
Steel 1
Steel 2
Steel 3

Results

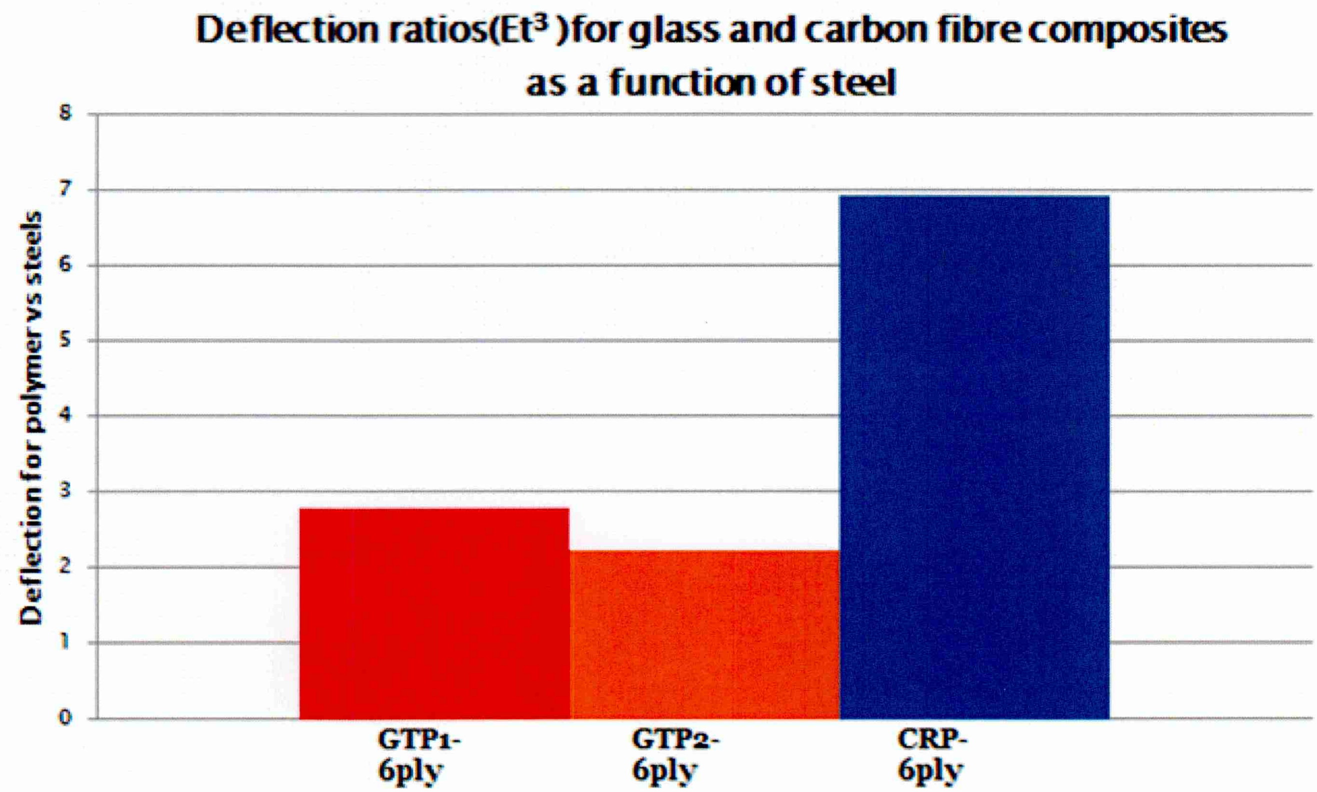


3 Point Bending Load at Break (N)
Load At Break (N)
600
500
400
300
200
100
0
GTP1 -6ply
GTP2 -6ply
CRP -6ply
GTP2 -5ply
GTP2 -4ply
steel1
steel2
steel3

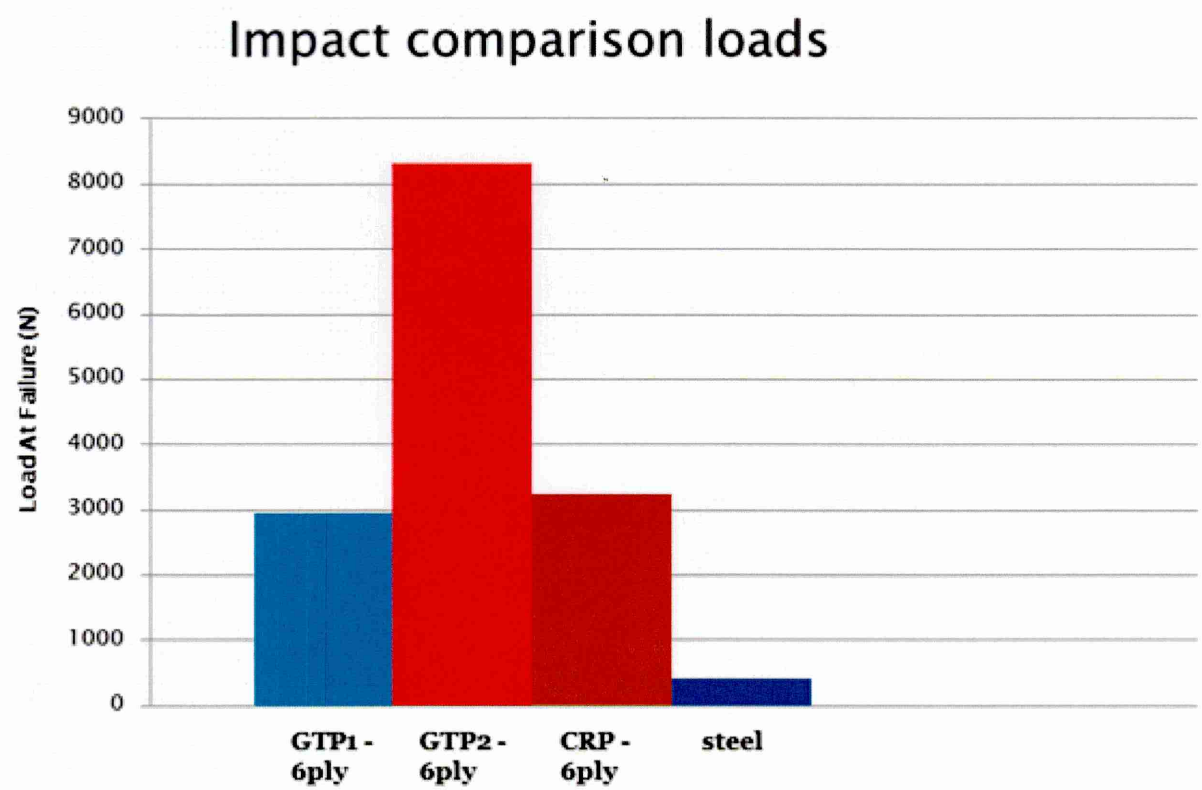
Results


Young's Modulus (MPa) per material
Young's Modulus (MPa)
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
GTP1 -6ply
GTP2 -6ply
CRP -6ply
Steel1/2/3

Results


Deflection ratios(Et³)for glass and carbon fibre composites as a function of steel
Deflection for polymer vs steels
0
1
2
3
4
5
6
7
8
GTP1-6ply
GTP2-6ply
CRP-6ply

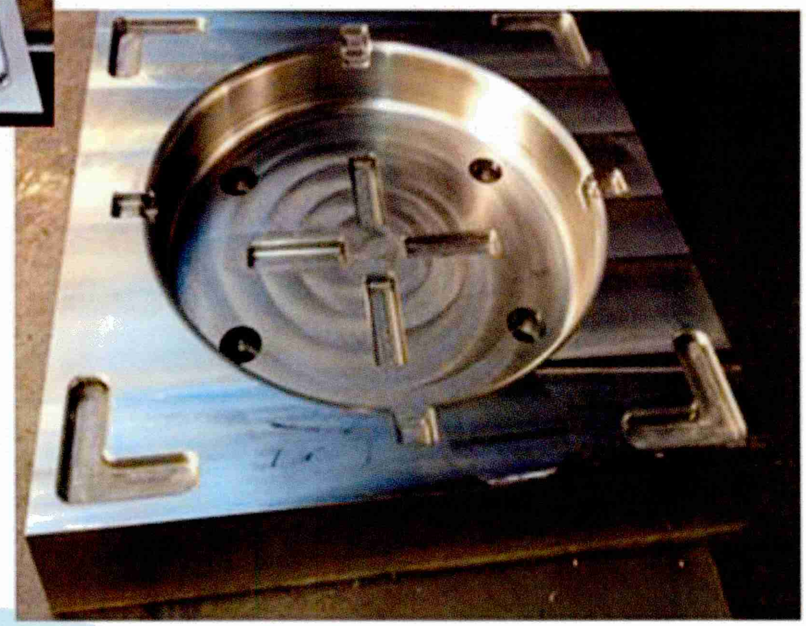
Results

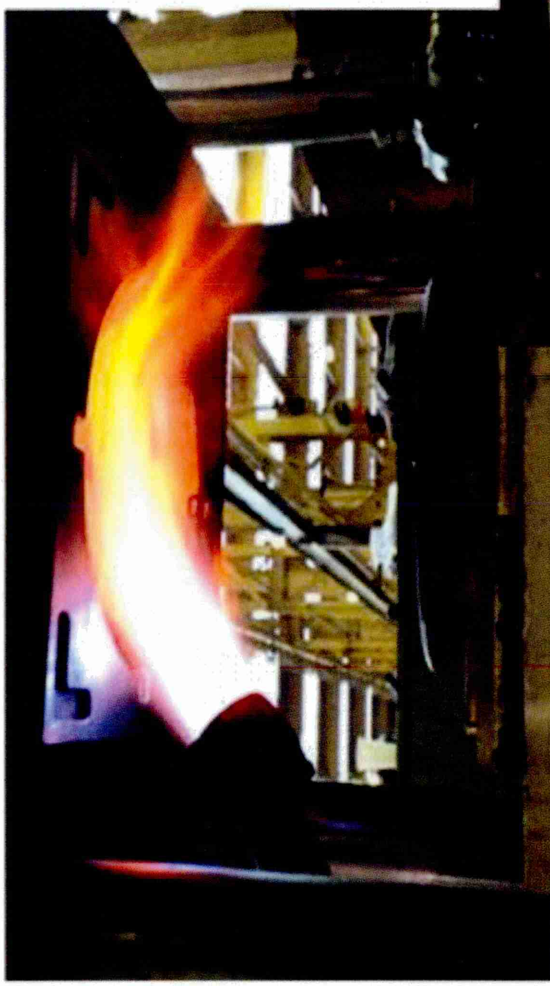


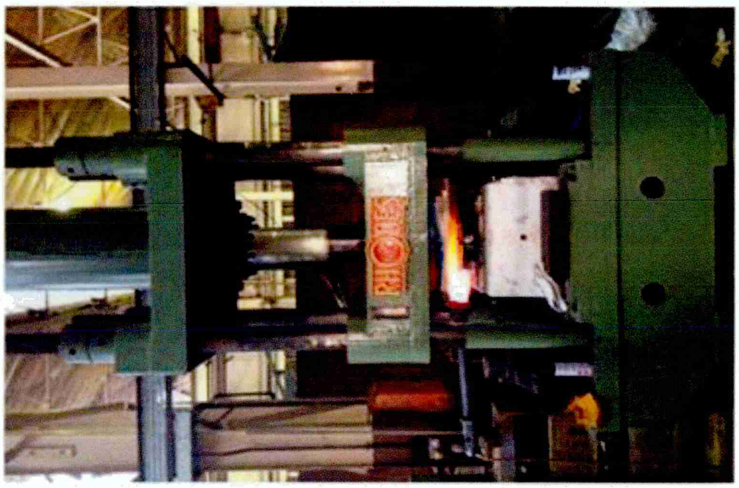
Impact comparison loads
Load At Failure (N)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
GTP1 - 6ply
GTP2 - 6ply
CRP - 6ply
steel

Scale Boot Pan

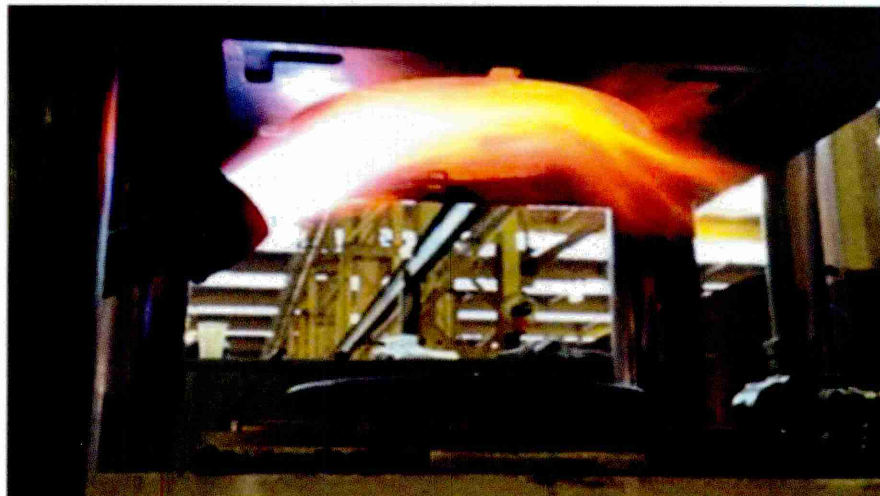
Automotive scaled boot pan press tool







Scale Boot Pan



100 tonne hydraulic press with pre-heated tooling

Commercial Feasibility

For tape speed of 40m/min and tape width of 350mm, laminate width=550mm, output speed = 12.73m/min.

For 24 hr/day , 7 days/week, 50 weeks/year operation, total linear production of 2 ply laminate = 6.4 million metres.

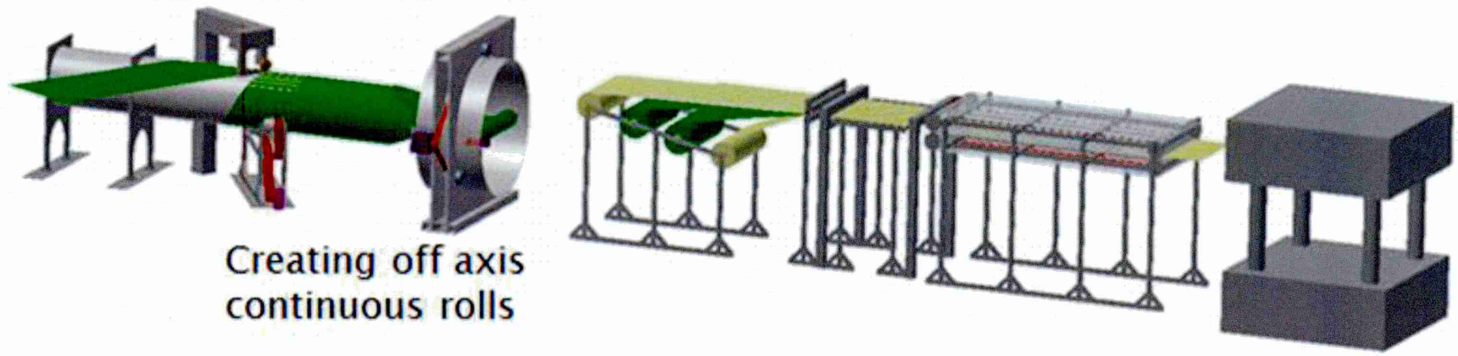
If machine capital cost is £350k, then annual processing cost = 10% interest + 10% capital + 10% operation + labour =£35k+£35k+£35k+£100K(labour) = £205k giving a cost/m of 2 ply laminate of £205k/6.4e6 = 3.2p/m or 5.8p/m^2

For single shift operation and 80% equipment availability, a 1m length of 6 ply sheet processing cost is 40p or 72.6p/m^2

Time saving

- 1000 part consolidated 6 ply laminates can be produced every 2hr 45mins = $1m^2$ / 9.9s
- with 5 ply laminates taking only 2hr 20mins = $1m^2$ / 8.4s
- This compares favourably to the time required for manual lay up.

Concept Model 1

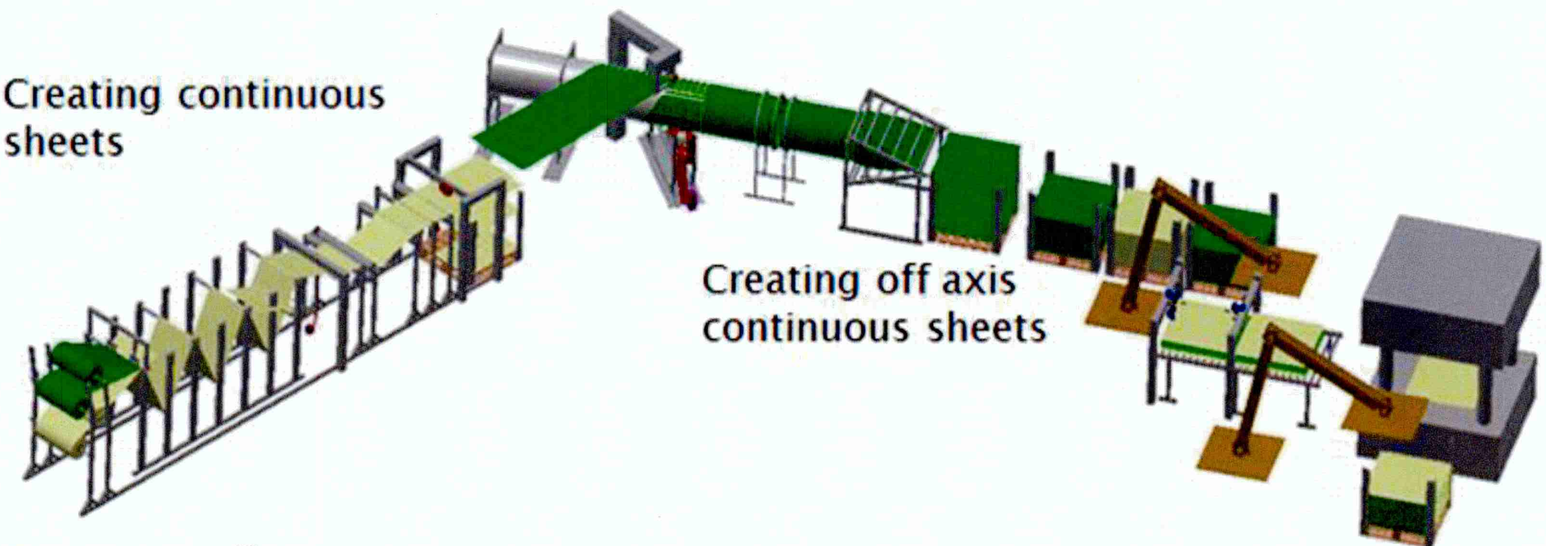


Creating off axis
continuous rolls

Pressed component

* Any size blank can be produced due to the concept being fully scalable for large components.

Concept Model 2



Production rate of $1m^2/9.9s$ ($6m^2/min$)

Fuel saving

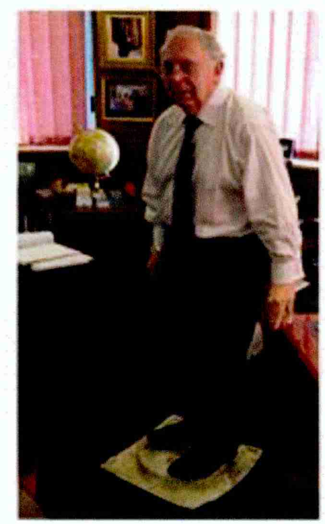
- On an average vehicle such as the 2012 Nissan Qashqai 2L diesel with an average mileage of 12,000 and a vehicle lifetime of 10 years.
- Fuel saving = 70L/year = 700L during the vehicle lifetime with a mass reduction of 100kg.
- Saving to individual = £1.40 x 700 = £978.60 over the life of the vehicle.
- Annual production volume of 190,000 = fuel saving of 13.3ML diesel per year – £18.89M.

*Fuel consumption based on data supplied by Nissan Motoring UK

Mass saving

- 5 Ply composite material reduces mass of several replacement components in excess of 50%
- Testing shows 5 Ply is the replacement orientation resulting in the following mass reductions

	Original panel	Composite panel	Mass saving (Kg)	Mass saving (%)
Spare Wheel Well	4.37Kg	1.81Kg	2.56Kg	58.60%
Roof Panel (glass)	4.53Kg	1.79Kg	2.74Kg	60.50%
Side Frame	11.6Kg	4.17Kg	7.43Kg	64.00%
Front Wing (each)	2.6Kg	1.29Kg	1.31Kg	50.40%



Cost

- Machine Cost
- Processing cost, and carbon footprint (wattage used during operation)

Fastening method

	Name of Samples	Failure Type	Tensile Test Load (N)	Peel Strength Test Load (N)
MECHANICAL FASTENING	SQUARE PLATE (5MM) *	Substrate	4354	938
	2-PIECE KNURLED BOLT (5MM) *	Substrate	3114	1098
	DOUBLE RIVET *	Substrate	2964	
	SINGLE RIVET *	Joint	1455	1335
	NORMAL BOLT WITH BIG WASHER (37MM)	Substrate	1156	-
	NORMAL BOLT	Substrate	-	2390
ADHESIVE FASTENING	SUPER GLUE (LOCTITE - HENKEL) *	Joint	1000	318
	J-FIX	Joint	383	-
	GORILLAZ'S SUPPER GLUE	Joint	347	-
	BIGHEAD	Joint	267	-
	PURAFLEX	Joint	84	-
	GORILLAZ'S GENERAL PURPOSE	Joint	-	-

- Mechanical single rivet proves to be best joining method for tensile load, ease of use, little mass, and cost.
- Maximum vehicle load – 565Kg (5543N).
- 4 equally spaced single rivets required.
- At 1455N the steel sub straight failed before the composite material (shown in the image below)

recycling

- Thermoplastic recycling options:
  - Remoulding
  - Separate fibre and matrix, to use as grog.
  - Grind end component for road filler.
  - Grind and burn in power station.
  - Grind to use as short fibre injection moulding.
  - Pyrolysis – fibre char, gas and oil.
  - chemically remove the matrix to create chemical and fibres.

References

1. www.ktponline.com
2. www.cperkin.co.uk
3. Ashby, Michael (1999), Materials Selection in Mechanical Design (3rd edition ed.), Burlington, Massachusetts: Butterworth-Heinemann, ISBN 0-7506-4357-9.

APPARATUS AND METHOD FOR PRODUCING A LAMINATE

FIELD OF INVENTION

The invention relates to apparatus and a method for forming a laminate from composite material, such as glass fibre reinforced polymer (GFRP) and carbon fibre reinforced composite (CFC). In particular, the invention relates to forming laminates which comprise one or more off-axis plies, wherein the laminates are formed from pre-impregnated (pre-preg) material.

BACKGROUND OF THE INVENTION

There is an increasing demand for components which are fabricated from composite materials such as GFRP and CFC. This is due to the excellent strength to weight ratio of these composites when compared to metal equivalents, and their potential for use in the automotive and defence industries.

Composite material is in general formed as a laminate, which comprises a plurality of individual plies that are sandwiched together, wherein the plies comprise a fibre and matrix component. To optimise the mechanical properties of the laminate it is desirable to have the fibres aligned at a range of angles, for instance 0^0, 90^0, $+45^0$, -45^0. These laminates are commonly hand laid and cured in an autoclave. This process does not lend itself to large scale manufacturing.

Apparatus for forming laminates with off-axis plies are known. For example, WO 2008/057146 discloses apparatus for producing a two layer off-axis composite material that has fibres at $\pm 5^0$. In more detail the apparatus of WO 2008/057146 is arranged such that pre-preg strips are dispensed from a plurality of supply rolls that are positioned on two application wheels. The application wheels are operable to counter rotate with respect to each other about a stationary mandrel. The pre-preg strips are wrapped around the mandrel, upon which they are pressed by rollers to form a tube. Thereafter, the tube is slid off the mandrel and slit, then opened to form a strip. The application wheels could be considered to be complicated and require precise alignment to achieve the desired fibre angle. Furthermore, the apparatus does not enable the formation of a laminate which comprises the off-axis plies and other orientations, such as 90^0 and 45^0.

An object of the present invention is to provide apparatus for forming a laminate with off-axis plies which overcomes one of the above or other problems. More specifically, an object of the present invention is to provide apparatus for forming a laminate with off-axis plies which is less complex.

SUMMARY OF THE INVENTION

According to a first aspect of the present invention there is provided apparatus to form off-axis composite material, the apparatus comprising:

a supply means to supply a strip of composite material, the strip comprising a matrix and a plurality of fibres, which are aligned to each other;

a stationary mandrel arranged to receive a portion of the strip from the supply means, the mandrel and supply means being arranged such that the strip is supplied to the mandrel with the fibres orientated off-axis to an elongate axis of the mandrel,

characterised in that a drive means is configured to drive the received strip to rotate about the mandrel, and to move axially along the elongate axis of the mandrel such that the strip forms a tube on the mandrel, the mandrel being configured to dispense the tube from an end of the mandrel such that the dispensed tube when pressed into a further strip or sheet has fibres which have an orientation that is off-axis in relation to the length of the further strip or sheet.

Preferably, the strip of composite material is a pre-preg strip.

Alternatively, the strip of composite material is any continuous fibre plastics material.

Alternatively, the strip of composite material is any long fibre plastics material.

Preferably, the drive means is arranged to engage a surface of the tube on the mandrel. Preferably, the drive means comprises a belt arranged to grip a portion of the tube, such that movement of the belt causes the tube to be moved relative the mandrel by the belt.

Preferably, the drive means further comprises a motor arranged to drive the belt, preferably via a gear assembly. Preferably, at least a portion of the belt extends between a first and second pulley, wherein the belt is arranged to engage the pre-preg tube between the first and second pulley. Preferably, a position of one or both of the first and second pulleys is adjustable such that the portion of the pre-preg tube which is engaged by the belt is adjustable, preferably to adjust the extent to which the belt extends around the mandrel, and / or the angle of the belt relative the elongate axis of the mandrel. Optionally, the drive means further comprises a flange which is operable to prevent the rotational and axial motion of the tube on the mandrel from disengaging the belt from at least one of the first and second pulleys.

Preferably, the supply means comprises a roll of composite material which is arranged to rotate relative a stationary support, preferably about an axis of rotation. Preferably, the axis of rotation is inclined to the elongate axis of the mandrel. Preferably, the stationary support is constrainable to the ground.

Preferably, the supply means is operatively connected to a second drive means, which is operable to drive the roll to rotate. Preferably, the second drive means comprises a motor arranged to drive the roll preferably via a gear assembly.

Preferably, the first and second drive means are controlled by a control unit. Preferably, the control unit is configured to actuate both of the first and second drive means to drive simultaneously. Preferably, the control unit is configured to actuate both of the first and second drive means to desist drive simultaneously.

Preferably, the composite material comprises unidirectional fibres in an uncured resin matrix. Preferably, the fibres of the composite material comprise carbon fibres or glass fibres.

Preferably, the matrix of the pre-preg material comprises one or more of the following materials: Polypropylene, PA6, PEEK and other thermoplastic materials.

Optionally, the fibres of the supplied strip of material of the supply means are aligned substantially to the length of the strip.

Alternatively, the fibres of the supplied strip of material are aligned substantially perpendicular to the length of the strip.

Preferably, the angle at which the fibres of the pre preg strip are supplied relative the elongate axis of the mandrel is between 5^0 to 85^0. More preferably, it is between 30^0 to 60^0. More preferably, it is about 45^0. Preferably, a position of the stationary support is adjustable such that the angle at which the fibres are supplied relative the elongate axis of the mandrel is adjustable, to thereby adjust the angle of the fibres in the further strip dispensed from the mandrel.

Preferably, the off-axis composite material comprises a lay-up being defined as a sandwich structure comprising a plurality of plies of composite strip or sheet.

Preferably, the strip or sheet dispensed from the mandrel comprises two plies, wherein the angle of the fibres in the first ply relative to a longitudinal axis of the mandrel is equal and opposite to the angle of the fibres in the second ply relative to a longitudinal axis of the mandrel. More preferably, the angle in the first ply is between $5^0 – 85^0$ with respect to a length direction of the strip (or a longitudinal axis of the mandrel), and the angle of the fibres in the second ply is between -5^0 to -85^0 with respect to a length direction of the strip or sheet (or a longitudinal axis of the mandrel). More preferably, it is about 45^0 and -45^0. More preferably, it is about 30^0 and -30^0.

Preferably, the supply means and the mandrel are configured such that the strip is wrapped around the mandrel to define the tube, preferably such a supplied portion of strip overlaps an adjacent portion of strip which is already received on the mandrel to define an overlap region. Preferably, the overlap region is about 10mm across the width of the strip, or about 0.5% - 5% of the width of the strip. More preferably it is about 11mm.

Preferably, the apparatus further comprises a welding element arranged to join a portion of the strip once received on the mandrel to an adjacent portion of strip on the mandrel to thereby form the tube. Preferably, the welding element is arranged to join the strip at the overlap region.

Preferably, the welding element comprises a hot air welder. Preferably, the apparatus further comprises a guide element arranged proximate the welding element to ensure the adjacent portions of strip are aligned prior to welding, preferably with the correct overlap.

Preferably, the apparatus further comprises a pressing element arranged to press the strip once received on the mandrel. Preferably, the pressing element is arranged proximate the welding element, preferably such that the adjacent portions of strip are pressed into alignment prior to welding and / or preferably such that the adjacent portions of strip are pressed downstream of the weld.

Optionally, the pressing element comprises a first roller disposed to press the overlap region against the surface of the mandrel.

Alternatively, the pressing element comprises a first roller disposed to press the overlap region against a second roller, wherein the second roller is disposed beneath the surface of the mandrel. Preferably, the mandrel comprises a hollow portion for housing the second roller.

Preferably, the apparatus is configured such that the pre-preg strip is wrapped around the mandrel to form a continuous tube on an outer surface of the mandrel. Preferably, the tube is a single ply thick.

Preferably, an outer surface of the mandrel is substantially cylindrical. Preferably, the mandrel is between 2 and 5 metres in length. More preferably, it is about 3.6 metres.

Preferably, the apparatus further comprises a heating element which is disposed proximate the supply means, which is operable to soften the strip once dispensed from the supply means.

Preferably, the mandrel comprises a receiving section for receiving the strip.

The mandrel may comprise a cutting section for cutting the tube into portions of a given length.

Preferably the mandrel comprises a dispensing section for dispensing the tube. Preferably, the dispensing section is positioned at a first end of the mandrel, and comprises a tapered section, the taper being arranged such that the diameter of the mandrel is narrower at its tip. Preferably, the receiving section is disposed between the first end and a second end of the mandrel.

Preferably the cutting section comprises a cutting ring disposed around the mandrel and preferably operable to move along an axis substantially identical to the axis of the tube.

Preferably the cutting ring is operable to move between a cutting start position and a cutting end position.

Preferably the cutting ring is operable to move from the cutting start position to the cutting end position to match an axial motion of the tube, whilst performing a cutting operation. Preferably the ring-shaped cutting unit is operable to move at a speed substantially identical to the axial motion of the tube whilst performing the cutting operation.

Preferably the cutting ring is operable to return to the cutting start position from the cutting end position whilst performing a return operation, such that the ring-shaped cutting unit is operable to start another cutting operation a fixed distance from the first end of the mandrel.

Optionally, the fixed distance is substantially equal to the width of the further sheet when compressed, so that a square-shaped further sheet may be formed. The fixed distance may be a direct result of one or more of the number of cutters, the mandrel diameter and the rotational speed of the tube being performed.

Preferably the cutting ring comprises one or more cutter heads. Preferably the cutting ring engages the cutter heads, thereby cutting the tube whilst performing the cutting operation. Preferably the cutting ring disengages the cutter heads whilst performing a return operation.

Preferably the cutter head comprises one or more rotatable cutting wheels disposed to cut in a direction substantially transverse to the longitudinal axis of the tube.

Preferably the or each rotatable cutting wheel is disposed so that the rotation of the tube forces the or each rotatable cutting wheel into the tube, thereby cutting the tube.

Alternatively, the cutting ring comprises one or more laser cutting elements. Alternatively, the cutting ring comprises one or more diamond-tipped cutting elements.

Preferably, the cut portions of the tube are propelled from the cutting section by the motion of the uncut tube along the mandrel.

Preferably, the drive means is disposed between the dispensing section and the welding element.

Preferably, the mandrel is supported at a second end in a cantilevered arrangement with respect to the ground.

Preferably, the apparatus further comprises a receiving means, which is operable to receive the tube once dispensed from the dispensing section of the mandrel.

Alternatively, the apparatus further comprises a flattening section for flattening the portions of tube dispensed by the cutting section.

Preferably, the receiving means comprises a roll which is rotatably mounted to a support structure. Preferably, the roll is rotatable about a rotational axis, which is orientated substantially perpendicular to the elongate axis of the mandrel. Preferably, the roll is rotatable by means of a third drive means, preferably, via a gear assembly, wherein the drive means is operable to effect rotation of the roll such that the tube is urged off the dispensing section and on to the roller of the receiving means.

Preferably, the control unit is configured to control the third drive means in accordance with the first and second drive means such that the dispensed strip is urged off the dispensing section and on to the roller of the receiving means.

Preferably, support structure is configured to enable rotation of the roller receiving means about an axis which is substantially aligned to the elongate axis of the mandrel. Preferably, the support structure is rotatable by means of a fourth drive means, preferably, via a gear assembly, wherein the fourth drive means is operable to effect rotation of the support structure such that it rotates with the tube to prevent twisting of the tube when dispensed from the dispensing section of the mandrel. Preferably, the control unit controls the fourth drive means such that the support structure rotates at substantially the same rate as the tube on the mandrel.

Preferably, the support structure comprises a drum arranged to rotate within a stationary support, wherein the roll is connected to the drum at a first and second point, such that the rotational axis of the roll extends across the diameter of the drum.

Preferably, a cutting element is disposed between the dispensing section of the mandrel and receiving roller, which is operable to cut the tube at a first and second point along a line parallel to the axis of rotation of the drum, wherein the first and second point are diametrically opposed to each other.

Preferably, an opening element is disposed between the cutting element and receiving roller, wherein the opening element comprises guide means, which are configured to guide the cut tube to a substantially flat strip prior to it being received by the receiving means.

Preferably, the opening element and cutting element are disposed on the drum such that they rotate with the drum.

Preferably, a pressing element is disposed between the dispensing section and receiving means, and preferably upstream and/or downstream of the cutting element which is configured to press the tube dispensed from the dispensing section prior to it being received by the receiving roller. Preferably, the pressing element is disposed on the drum such that it rotates with the drum.

Preferably, the flattening section comprises a plurality of pairs of rollers. Preferably, the rollers in each pair are disposed at opposite sides of an elongate axis of the tube,

Preferably, the rollers are aligned transversely with respect to the axis of the tube. Preferably, the rollers in each pair are positioned in the same vertical longitudinal plane. Preferably, the plurality of pairs of rollers are positioned successively from a receiving end, closest to the cutting section, and a dispensing end, furthest from the cutting section.

Preferably, the distance between the rollers in each of the plurality of pairs of rollers decreases successively from the receiving end to the dispensing end, so that a tube propelled through the flattening section is progressively flattened, so that a sheet comprising two plies, wherein the angle of the fibres in the first ply is equal and opposite to the angle of the fibres in the second ply, is formed.

Preferably, the axial motion of the tube propels the tube through the flattening section, forcing the tube to be flattened by each of the plurality of pairs of rollers.

Preferably, the outer surface of the mandrel comprises an outer surface which permits relative movement of the tube on the mandrel, preferably the outer surface comprises Teflon coating.

Preferably, the off-axis strip dispensed by the mandrel comprises a 2 ply strip with a first strip having fibres which are positively angled with respect to the length of the strip, and a second strip having fibres which are negatively angled with respect to the length of the strip.

Preferably, the apparatus comprises a bonding section, operable to bond together a plurality of sheets of composite material dispensed by the flattening section to form a single multi-ply sheet. Preferably the material bonded comprises both 2-ply off-axis composite material dispensed by the flattening section and on-axis composite material.

Preferably, the plies are arranged so that the orientation of the fibres in the plies from a top ply to a middle ply is identical to the orientation of the fibres in the plies from a bottom ply to a middle ply.

Preferably the material bonded has 3 layers, whereby the central layer is a single ply of on-axis composite material and the other layers are 2-ply off-axis composite material dispensed from the flattening section,

Alternatively, any odd number of layers may be bonded, whereby the orientation of the fibres in the plies from a top ply to a middle ply is identical to the orientation of the fibres in the plies from a bottom ply to a middle ply.

Preferably, the material is bonded by ultrasonic welding. Preferably, the material is bonded at a plurality of bond points. Preferably, the bond points are located approximately ¼ of the width away from the edge and the top edge.

According to a second aspect of the invention there is provided a method of forming off-axis composite material, the method comprising:

supplying a strip of composite material from a supply means to a stationary mandrel, the strip comprising a matrix and a plurality of fibres, which are aligned to each other, wherein the mandrel and supply means are arranged such that the pre-preg strip is supplied to the mandrel with the fibres orientated off-axis to an elongate axis of the mandrel,

characterised in that the method comprises a step of using a drive means to drive the received strip to rotate about the mandrel, and to move axially along the elongate axis of the mandrel such that the pre-preg strip forms a tube on the mandrel;

and a step of dispensing the tube from an end of the mandrel such that the dispensed tube when pressed into a strip or sheet has fibres which have an orientation that is off-axis in relation to the length of the strip or sheet.

Preferably, prior to supplying the strip to the mandrel, the method includes a step of joining a plurality of strips pre-preg material to form a wider strip of material, the wider strip of material being dispensed by the supply means. Preferably, the method includes a step of joining a first strip of material to a second strip of pre-preg material to form a wider strip of material.

Preferably, the first strip is dispensed from a roll which is rotatably mounted on a first stationary support, and the second strip is dispensed from a roll which is rotatably mounted on a second stationary support, wherein the first and second strips are fed adjacent to each other into a pressing element, preferably, such that the first and second strips overlap by about 5mm - 20 mm. Preferably, the pressing element comprises a plurality of rollers which are configured to press the first and second strip together at the overlap. Preferably, a welding element is arranged to weld the first and second strip together at the overlap, preferably the welding element is positioned upstream of and / or downstream of and / or between the rollers of the pressing element.

Preferably, the method includes a step of wrapping the strip around the mandrel to form a tube of strip.

Preferably, the method includes a step of joining a portion of the strip once received on the mandrel to an adjacent portion of strip already on the mandrel by means of a welding element.

Preferably, the method includes a step of dispensing the tube from a dispensing section of the mandrel, wherein the dispensing section comprises a tapered section, the taper being arranged such that the diameter of the mandrel is narrower at its tip.

Preferably, the method includes a step of collecting the dispensed strip as a roll on a receiving means, the roll having an axis of rotation which is oriented substantially perpendicular to the axis of rotation of the mandrel.

Alternatively, the method includes a step of cutting the tube into sections using a cutting section. Alternatively, the method includes a step of flattening the cut sections of tube to form sheets.

Preferably, the step of collecting the dispensed strip includes a step of rotating the roll about an axis aligned to the elongate axis of the mandrel by means of a rotatable support structure.

Preferably, the method further comprises a step of laying one or more further strips with the strip of the roller of the receiving means to form a composite lay-up, the method comprising:

arranging a roll of the or each further strip adjacent a roll from the receiving roller, such that the strip from the receiving roller and the or each further strip when dispensed are laid together when received by a pressing element, the pressing element preferably comprising a plurality of rollers. Preferably, the or each further strip comprises strip material arranged with the fibres orientated differently to the fibres of the strip from the receiving roller. Preferably, the method further includes a step of part consolidating the strips together by means of a welding element, which is disposed downstream of the pressing element.

Alternatively, the method further comprises a step of bonding a plurality of sheets of composite material, the method comprising:

arranging a plurality of sheets dispensed by the flattening section into layers, bonding the layers together using ultrasonic welding.

Preferably the material bonded comprises both 2-ply off-axis composite material dispensed by the flattening section and on-axis composite material. Preferably, the plies are arranged so that the orientation of the fibres in the plies from a top ply to a middle ply is identical to the orientation of the fibres in the plies from a bottom ply to a middle ply.

Preferably the material bonded has 3 layers, whereby the central layer is a single ply of on-axis composite material and the other layers are 2-ply off-axis composite material dispensed from the flattening section,

Alternatively, any odd number of layers may be bonded, whereby the orientation of the fibres in the plies from a top ply to a middle ply is identical to the orientation of the fibres in the plies from a bottom ply to a middle ply.

Preferably, the material is bonded at a plurality of bond points. Preferably, the bond points are located short distance from an edge or corner of the material. Preferably, there are four bond points, each located proximate to a corner of the material.

All of the features described herein may be combined with any of the above aspects, in any combination.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the invention, and to show how embodiments of the same may be carried into effect, reference will now be made, by way of example, to the accompanying diagrammatic drawings in which:

Figure 1 shows a perspective view of apparatus for forming a laminate of off-axis composite material according to an exemplary embodiment of the invention;

Figure 2 shows a perspective view of a guide element of the apparatus of figure 1;

Figure 3 shows a perspective view of a drive means of the apparatus of figure 1;

Figure 4 shows a perspective view of a receiving means and rotary support structure of the apparatus of figure 1;

Figure 5 shows a perspective view of a cutting element and opening element of the apparatus of figure 1;

Figure 6 shows a perspective view of apparatus for joining strips of composite material;

Figure 7 shows a perspective view of apparatus for forming a lay-up of composite material;

Figure 8 is a schematic perspective view of an alternative cutting section of the apparatus;

Figure 9 is a schematic end view of the alternative cutting section; and

Figure 10 is a schematic side view of an embodiment of the apparatus incorporating the alternative cutting section.

DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENTS

Figure 1 shows an exemplary embodiment of apparatus 100 for forming a laminate of pre-preg composite material. The apparatus comprises supply means 200 to supply pre-preg strip 400 to a stationary mandrel 300. The pre-preg strip 400 is formed into a tube 410 on the mandrel 300, and is driven to both rotate relative to the mandrel and to move axially along the mandrel. In this way it can be dispensed from an end of the mandrel 300 and formed in to a further pre-preg strip 420 with off-axis fibres, as will be discussed in more detail below.

Firstly considering the supply means 200, in this example the supply means 200 comprises a roll 210 of the pre-preg strip 400, which is rotatably mounted to a support 220. It will be appreciated that other configurations of supply means are possible, for instance, the pre-preg strip 400 may be directly fed to the mandrel 300 in strip form from a conveyor, thus obviating the need for an intermediate roll 210. However, referring back to the present configuration, the roll 210 is connected to the support 220 at its ends, and is operable to rotate about an axis of rotation 230. The support 220 remains stationary in use, however the orientation of the axis of rotation 230 can be adjusted relative to an elongate axis of the mandrel 300. Such adjustment is used to change the orientation of the fibres on the tube 410 and strip 420 as will be discussed in more detail below.

In one example, rotation of the pre-preg tube 410 about the mandrel 300 causes the pre-preg strip 400 to be pulled from the roll 210, such that it is dispensed onto the mandrel without the need for the drive means 240 as discussed below. However, in this example, the roll 210 is operatively connected to drive means 240, which is operable to drive the roll 210 to rotate. In more detail, the drive means 240 comprise a motor (not shown), which is arranged to drive the roll 210 via a gear assembly (not shown). The drive means 240 is optionally configured to drive the roll 210 upon actuation of separate drive means 800 which is operable to cause rotation tube 410 on the mandrel 300. Such an arrangement is achieved by means of a control unit 500 (not shown), which is connected to and controls operation of both the drive means 800 and 240. An advantage of the drive means 240 is that it reduces the tensile force on the pre-preg strip 210, in comparison to an arrangement where the pre-preg strip 210 is dispensed from the roll 220 solely by force provided by rotation of tube 410 on the mandrel 300. The control unit 500 is also configured to control the drive means 240 to prevent excessive rotation of the roll 210 once rotation of the tube 410 has been stopped and / or reduced by the drive means 800. In this way excessive unrolling of the roll 210 is prevented.

The rate of rotation of the roll 210 is controlled by the control unit 500 (via the drive means 240) such that a constant feed rate of pre-preg strip 400 is maintained. For instance, as the amount of pre-preg strip 400 on the roll 210 decreases, the diameter at the periphery of the roll is decreased, accordingly, to compensate, the control unit 500 (not shown) increases the rate of rotation of the roll.

Now considering the mandrel 300 in more detail. The mandrel 300 is elongate about an axis 302 and has a proximal end 310 and a distal end 330. Between the proximal and distal ends 310, 330 there exists a cylindrical forming portion 350 for receiving the pre-preg strip 400, and upon which the tube 410 is formed.

At the proximal end 310 the mandrel 300 is supported by structural supports 312A, 312B, which maintain the mandrel 300 in a fixed position that is substantially horizontal with respect to the ground.

At the distal end 330 the mandrel 300 comprises a dispensing portion 332 that has a taper arranged to taper from the diameter of the forming portion 350 to a smaller diameter. In this embodiment the outer surface tapers such that it is inclined at about 20° to the axis of symmetry of the mandrel. However, it will be appreciated that other suitable angles may be used.

The pre-preg strip 400 is supplied to the mandrel 300 such that it is wrapped around the forming portion 350 of the mandrel to form the tube 410. In more detail, the pre-preg strip 400 is wrapped around the mandrel such that a subsequently laid portion 400A is partially overlaid on top of, and along an edge of a portion 400B of the pre-preg strip 400 which has already been laid on the forming portion. Accordingly, an overlap region 412 is created, which is typically 5 – 20 mm in width, however it will be appreciated that different quantities of overlap may be used depending on the overall width of the pre-preg strip 400 and size of the mandrel 300.

In one example, the forming surface 350 of the mandrel 300 comprises a non-stick coating which permits relative movement of the pre-preg tube 410 on the mandrel 300. An example of such a coating is Teflon.

A welding element 600 is arranged to weld the portions 400A and 400B together at the overlap region 412. In more detail the welding element comprises a hot air welder operable to supply hot air which is about 650^{0}C to the overlap region 412. The hot air causes the portions 400A and 400B to be consolidated / partly consolidated together.

A pressing element 700 is disposed proximate the welding element 600 and is operable to press the overlap region 412 such that it is correctly aligned / consolidated. In this example the pressing element comprises a first roller 710A, which is positioned external the mandrel 300, and a second roller 710B (not shown), which is positioned within the mandrel 300. The rollers 710A, 710B are orientated such that their axis of rotation is substantially perpendicular to the edge of the overlap region 412, and are orientated such that the overlap region 412 is fed between them as the tube 410 is rotated on the mandrel. It will be appreciated that in another example the pressing element 700 may comprise only the first roller 710A which is arranged to press the overlap region 412 against the forming surface 350 of the mandrel 300.

In this example the pressing element 700 is arranged to press the overlap region 412 after it has been welded, hence downstream of the weld. However, in other examples it will be appreciated that the pressing element 700 can be additionally or alternatively positioned to act on a portion of the overlap region 412 which is upstream of the weld.

Figure 2 shows a guide element 750 which is designed to ensure the pre-preg strip 400 is correctly aligned at the overlap region 412 prior to welding. In more detail the guide element comprises an 'S' shaped formation, with a first channel 752 for receiving the pre-preg strip 400A to be received on the mandrel 300, and a second channel 754 for receiving the pre-preg strip 400B which is already on the mandrel. As shown, the channels 752, 754 extend in opposed directions, and the first channel 752 is arranged with its inlet 752 aligned to the feed of strip from the supply means 200 to receive the pre-preg strip directly from it, whereas the inlet 755 of the second channel is aligned to receive the strip 400B as it rotates on the mandrel. Such an arrangement is achieved by connecting a portion of the second channel 754 to the mandrel. An advantage of the guide element is that the gap 756 between the channels 752, 754 allows hot air from the welder to travel between the strips 400A, 400B immediately after the strips exit the guide element 750. Such an arrangement improves the efficiency of the welding process.

As best seen in figure 3, a drive means 800 is arranged in operational proximity to the forming surface 350 of the mandrel 300 such that it can drive the tube 410 to rotate relative the mandrel 300, and drive the tube 410 to displace axially along the mandrel 300. In more detail, the drive means 800 comprises a first belt 810 which extends around a first pulley 820, a second pulley 830 a third pulley 840 and a fourth pulley 842, all of which are rotatably mounted to a stationary support 850. A motor 860, which is also attached to the stationary support 850, is arranged to drive the fourth pulley 842 via a second belt 870 and a gear assembly (not shown) such that the desired rotational speed is obtained. The first and second pulley 820, 830 are arranged such that the belt 810 both extends circumferentially around the forming portion 350 and partially extends along the elongate axis 302 of the mandrel 300. In this way, the belt 810 is operable to grip the tube 410 and drive it to both rotate about the elongate axis 310 of the mandrel and to move along the elongate axis 310 of the mandrel 300. Such driving of the tube 410 causes the pre-preg strip 400 to be dispensed from the supply means 200 and subsequently formed as part of the tube 410, as will be described in more detail below.

In this example and as best seen in figure 1 the belt 810 extends around a lower surface of the mandrel, however it will also be appreciated that the same effect can be achieved by arranging the belt to extend around the sides or top of the mandrel 300.

The position of first and second pulleys 820, 830 is adjustable by moving the stationary support 850, for instance in a height direction and also along the ground. In this way the angle at which the belt 810 grips the tube 410, and the extent to which the belt 810 grips the tube can be adjusted. Accordingly, the position of the fourth pulley 842 is also adjustable relative the stationary support 850 such that it can take up the slack in the belt 810 which occurs by adjustment of the positions of the first and second pulleys 820, 830.

Although an example of drive means 800 which has four pulleys has been shown, it will be appreciated that other configurations of drive means 800 are possible, for instance, the drive means 800 may be configured without a third pulley.

In the instance where the fibres are arranged such that they are aligned to the length of the strip, the stationery support 850 is positioned relative the mandrel 300 such that the belt 810 is aligned to the fibres in the composite material that forms the tube 410. However, it will be appreciated that in the instance where the fibres in the strip are normal to its length, the belt is perpendicular to the fibres.

As best seen in figures 1 and 4 a receiving means 900 is disposed proximate the distal end 330 of the mandrel 300 and is arranged to receive the strip 420 once dispensed from the tapered dispensing portion 332 of the mandrel. In more detail, the receiving means 900 comprises a roll 910 of the pre-preg strip 420, which is rotatably mounted to a drum 1010 of a rotary support structure 1000, as will be discussed in more detail below. It will be appreciated that other configurations of receiving means are possible, for instance, the pre-preg strip 420 may be directly fed from the mandrel 300 to a conveyor, thus obviating the need for an intermediate roll 910. However, referring back to the present configuration, the roll 910 is connected to the drum 1010 at its ends, across the diameter of the drum, and is operable to rotate about an axis of rotation 930. The drum 1010 rotates about the elongate axis 302 of the mandrel in use, as will be discussed in more detail below, however during this rotation the axis of rotation 930 of the roll 910 remains substantially perpendicular to the elongate axis 302 of the mandrel 300.

The roll 910 is operatively connected to drive means 940, which is operable to drive the roll 910 to rotate. In more detail, the drive means 940 comprise a motor (not shown), which is arranged to drive the roll 910 via a gear assembly (not shown). The drive means 940 is optionally configured to drive the roll 910 upon actuation of the drive means 800 which is operable to cause rotation tube 410 on the mandrel 300. Such an arrangement is achieved by means of the control unit 500, which is connected to and controls operation of both the drive means 800 and 940. The control unit 500 is also configured to control the drive means 940 to prevent rotation of the roll 910 once rotation of the tube 410 has been stopped by the drive means 800. In this way excessive unrolling of the roll 910 is prevented.

The rate of rotation of the roll 910 is controlled by the control unit 500 (via the drive means 940) such that the roll 910 can receive the pre-preg strip 420 at a constant feed rate. For instance, as the amount of pre-preg strip 420 on the roll increases, the diameter at the periphery of the roll is increased, accordingly, to compensate, the control unit 500 decreases the rate of rotation of the roll.

A rotary support structure 1000 is arranged to house the receiving means 900. In more detail, the rotary support structure 1000 comprises a rotatable drum 1010 that is arranged to rotate within a stationary support 1020. The drum 1010 is arranged about an axis 1002 which is aligned to the elongate axis 302 of the mandrel.

The drum 1010 is operatively connected to drive means 1040, which is operable to drive the drum 1010 to rotate. In more detail, the drive means 1040 comprises a motor (not shown), which is arranged to drive the drum 1010 via a gear assembly (not shown). The drive means 1040 is optionally configured to drive the drum 1010 upon actuation of the drive means 800 (which is operable to cause rotation of the tube 410 on the mandrel 300). Such an arrangement is achieved by means of the control unit 500, which is connected to and controls operation of both the drive means 800 and 1040. The control unit 500 is also configured to control the drive means 1040 such that the drum 1010 rotates at the same rate as the tube 410 on the mandrel 300. In this way twisting of the tube 410 is prevented as it is transferred from the mandrel 300 to the receiving means 900.

As best seen in figure 5 a cutting element 1100 is disposed on the drum 1010, such that it rotates with the drum 1010, and is positioned between the dispensing section 332 of the mandrel 300 and the receiving means 900. The cutting element 1100 comprises two blades 1110A, 1110B (not shown) which are arranged to cut the pre-preg tube 410 into the strip 420. In more detail, the blades 1110 are positioned to be in line with the axis of rotation 930 of the receiving means 900, and are positioned symmetrically with respect to each other about the axis 1002 of rotation of the drum 1010. The blades are orientated such that the cutting portion is normal to and extends through the side of the tube 410. In this way, as the tube 410 is fed towards the receiving means 900 it is cut by both blades 1110A, 1110B along two lines which are parallel to the axis of rotation of the drum 302 and converted into two strips 420A, 420B.

An opening element 1200 is disposed on the drum 1010, such that it rotates with the drum 1010, and is positioned between the cutting element 1100 and the receiving means 900. The opening element 1200 comprises two guides 1210A, 1210B (not shown) which are arranged to guide the cut pre-preg tube 410 such that it is re-shaped into a substantially planer strip 420 that is suitable for being rolled on the roller 910 of the receiving means 900. In more detail, the guides 1210 are positioned to be in line with the axis of rotation 930 of the receiving means 900, and are positioned symmetrically with respect to each other about the axis 1002 of rotation of the drum 1010.

Notably, the diameter of the drum 1010 is greater that the diameter of the mandrel 300. Such an arrangement is to enable the tube 410 dispensed from the mandrel to be fully opened into the planer strips 420A, 420B within the drum 1010.

As best seen in figures 1 and 5 a pressing element 1300 (not shown) may be disposed between the cutting element 1200 and the receiving means 900 and in addition or alternatively, further pressing elements may be positioned between the cutting element and dispensing portion 330 of the mandrel 300. The pressing element 1300 comprises two counter rotating rollers 1310A, 1310B (not shown) which are attached to the drum 1010 such that they rotate with the drum 1010. The rollers 1310A, 1310B arranged on either side of the cut pre-preg strip 420A 420B such that as the pre-preg strip 410 passes between the rollers 1310A, 1310B, it is pressed prior to it being received by the receiving roller 910.

An alternative embodiment of the cutting section is shown in Figures 8, 9 and 10. The alternative cutting section shares the rotary support structure 1000 with the previous embodiment but has a different cutting means 2000 comprising a cutting ring 2010 mounted on lateral supports 2012a and 2012b. A motor 2014 drives a belt 2016 that drives the cutting ring 2010 along the lateral supports 2012 at a speed matching the progression of the tube 410 of pre-preg material. Cutter heads 2018a, b, c, d, e, f, g and h are located on the cutting ring 2010 and as can be seen in Figure 9 protrude inwards of an inner periphery of the cutting ring to allow engagement with the tube 410 to allow cutting thereof. The belt 2016 may drive the engagement/disengagement of the cutter heads 2018a-h.

In order to cut the tube 410 perpendicular to its longitudinal axis it is necessary to move the cutting ring at the same speed as the tube 410 progresses along the mandrel. Matching of the speed of the motor 2014 to ensure progression of the cutting ring 2010 at the same speed as the tube 410 allows the position of the cut to remain fixed with respect to the longitudinal axis of the tube. Movement of the cutting ring 2010 around the longitudinal axis of the mandrel (and also the tube 410) allows the cutting heads 2018 to produce a cut whilst the tube 410 is formed and moved along the mandrel.

The cutting operation must be performed during the progression of the tube 420 from the right hand end of the lateral supports 2012a and 2012b shown in Figure 8 to the left hand end of those supports. During this time the cutting ring 2010 is driven along the lateral supports 2012a and 2012b to perform the cutting. When the cutting has been finished then the cutting heads 2018 are disengaged and the cutting ring 2010 is returned to the right hand end of the lateral supports 2012 as shown in Figure 8 for the cutting of another section of the tube 410.

As the cut section of tube progresses out of the cutting means 2000 (on the left hand end as shown in Figure 8) it proceeds to a flattening section 2500. The flattening section 2500 as shown in Figure 10 provides a narrowing wedge-shaped space into which the cut section of tube 410 is pushed by the driving means 800. The flattening section 2500 comprises sets of rollers 2510 that are placed in a progressively narrowing formation to urge the cut tube shape into a flattened two-ply sheet 2600 formed of the pre-preg strip 400. It will be understood that the flattened two-ply sheet 2600 consists of a first layer having an off-axis alignment with fibres aligned at a symmetrically negative angle to the longitudinal axis of the mandrel. The two layers may be separated and used in creating a multi-ply material, perhaps with an on-axis central layer of the material with the off-axis layers referred to above located on either face of the on-axis material.

Based on the length of the tube 410 that is cut by the cutting means 2000, rectangular or square sections of the off-axis material will be produced by the machine described herein. These off-axis layers of material can be laid up with on-axis layers and also layers of varying degrees of off-axis alignment to produce a material that has excellent strength properties in multiple directions and, for example, has a significantly lower weight than steel, but with corresponding or improved strength characteristics.

It is noted that multi-ply sheets in which the orientation of the fibres in the plies from a top ply to a middle ply is identical to the orientation of the fibres in the plies from a bottom ply to a middle ply have been found to have excellent strength characteristics.

For example, a 3 layer/5 ply material may be formed, whereby the central layer is a single ply of on-axis composite material and the other layers are 2-ply off-axis composite material dispensed from the flattening section 2500, It will be understood that any odd number of layers may be bonded in a similar manner to produce very strong material.

The off-axis panels can suitably be supplied in 1 m^2 sections, either in a single off-axis layer or in multiple layers as described above. The layers described herein may be welded together with suitable ultrasonic welding or other forms of welding as appropriate to the material from which the tube 410 is formed.

In one example, the material is ultrasonically welded at four bond points, each located towards a corner of the sheet, and approximately ¼ of the width of the sheet away from the edges of the sheet.

Considering the material of the pre-preg strip 400, this may be any formation of pre-preg material which is known in the art. In more detail, the material comprises unidirectional fibres in an uncured resin matrix. The fibres are typically carbon fibres or glass fibres, and the matrix typically comprises one or more of the following materials; a thermoplastic

The fibres are orientated such that they are aligned in the width direction of the strip 400 (for instance, the fibres are parallel to the axis of rotation 230 of the roll 210, when rolled), however it will be appreciated that the fibres can also be aligned along the length direction of the strip.

Since the support 220 is positioned such that the axis of rotation 230 of the roll 210 of strip 400 is an angle to the elongate axis 302 of the mandrel 300, the fibres in the strip 400 are fed at an angle to the elongate axis 302 of the mandrel 300, typically this angle is about 60°. Therefore, as the strip 400 is formed into a tube 410 on the mandrel, it will be appreciated that the fibres are arranged to form a helix.

Accordingly, as the tube 410 is cut and pressed flat to form the 2 ply strip 420 the fibres in the first ply 420A are positively angled with respect to the length of the strip, and the fibres in the second ply 420B are negatively angled with respect to the length of the strip. In this way, the roll 910 of the receiving means collects a two ply thick strip with an angled ply orientation. It will be appreciated that as the angle of the support 220 is adjusted to change the alignment of the axis of rotation 230 with the elongate axis 302, the angle of the fibres in the plies 420A, 420B is adjusted. Generally, the apparatus is configured to produce a strip with fibres which are +45/-45, or +30/-90 although it will be appreciated that a range of angles are possible.

A method of using the apparatus 100 will now be described with reference to the above description. The pre-preg strip 400 is supplied from the roll 210 of the supply means 200 to the forming section 350 of the mandrel 300. This is achieved by simultaneous actuation of both the drive means 230 of the supply means 200, and of the drive means 800 proximate the mandrel 300. The pre-preg strip 400 is then wrapped around the mandrel 300 to form a tube 410. The tube is fixed together at the overlap region 412 by the welding element 600 and pressing element 700. Downstream, the drive means 800 grips the tube 410 and causes it to rotate around the mandrel and to move axially along the mandrel such that it is dispensed from the mandrel 300. Thereafter, the tube 410 is cut by the cutting element 1100 and opened into a strip 420 by the opening element 1200. The strip 420 is then collected as a roll 910 on the receiving means 900.

Once the roll 910 becomes full, the drive means 230, 800, 940 and 1040 are stopped. The strip 420 is then cut proximate the roll 910 to enable removal of the roll. The roll 910 is then replaced and the strip 420 is attached to the new roll. The drive means 230, 800 and 1000 can then be re-started and the forming process continued.

Once the roll 210 of the supply means 200 becomes empty, the drive means are stopped and the old roll 210 is replaced by a new roll and the strip of the new roll fastened to the end of the strip of the old roll.

To initiate the process described in figure 1, firstly a strip from the supply means 200 is manually placed on the mandrel 300. The strip is then manually wrapped around the mandrel 300 to form the tube 410. The tube is manually rotated on the mandrel 300 until it engages with the drive means 800. Thereafter, the drive means is used to rotate the tube until it is dispensed from the mandrel 300. The dispensed tube 410 is then manually guided through the cutting element 1100 and pressing element 1300 and attached to the receiving means 900. Thereafter, the process can be automated using the control unit 500 and associated drive means: 240, 800, 940, 1040.

Prior to the process described in the above and in figure 1, a plurality of strips can be formed together by the process illustrated in figure 6, as will be discussed in more detail below.

Accordingly, with reference to figure 6a, and as part of the process 1500, a first strip 1510 is joined to a second strip 1520, to form a wider third strip 1530. In more detail, the first strip 1510 is arranged on a first roll 1512, and the second strip 1520 is arranged on a second roll 1522. An axis of rotation of the first roll 1514, and an axis of rotation of the second roll 1524 are aligned to each other, and are arranged such that the axis 1524 is forward of and below the axis 1514. In this way, when both strips 1510, 1520 are fed into a pressing element 1540, the strip 1510 is positioned above and can partially overlap the strip 1520 to create an overlap region 1512 which extends along the edges of the strips.

The pressing element 1540 comprises a plurality of rollers 1542, 1544, 1546 which are arranged to guide and press the strips together at the overlap region 1512. In more detail, the roller 1542 is arranged to receive the strips 1510, 1520 and guide them between the rollers 1544, 1546, which are driven to counter rotate and provide a pressing force by the drive means 1560.

Downstream, further rollers 1548 and 1550 receive the strips 1510, 1520 and are arranged on either side of a welding element 1570. The welding element 1570 acts to weld the strips 1510, 1520 together at the overlap region 1512 to form the strip 1530. The welder 1570 is a hot air welder and is equivalent to the welder 600 as described in the above.

The strip 1530 is then collected as a roll 1532, which is driven to rotate by drive means 1534. The roll 1532 when full can be removed by cutting the strip 1530. The removed roll can then be attached to the stationary support 230 to form the roll 210 of apparatus 100, as shown in figure 1. Alternatively, the rolls 1532, 210 may be dispensed with and the strip 1530 fed directly to the mandrel 300 as the strip 400.

Optionally, the width of the strip 1530 is further increased by repeating the process shown in figure 6a, such that two strips 1530 (not shown) are joined to form a wider strip 1536 (not shown).

Typically, a strip of a single roll is about 3.5cm in width, hence two strips joined together are about 7.0cm in width, although it will be appreciated that other sized strips may be used.

Following the process in accordance to the apparatus 100 of figure 1, the strip 430 can be merged with other layers of strip by the process 2000 illustrated in figure 7, as will be discussed in more detail below.

Accordingly, with reference to figure 7, and as part of the process 2000, two portions of the strip 430A, 430B are arranged to sandwich further portions of strips 2010A, 2010B. In more detail, the strips 430A, 2010A, 2010B and 430B are arranged on respective rolls 2012A, B, C, D. The respective axis of rotation 2014A, B, C, D of the rolls 2012 are aligned to each other and are arranged such: that the axis 2012B is forward of and below the axis 2012A; axis 2012C is forward of and below the axis 2012B; axis 2012D is forward of and below the axis 2012C. In this way the strips 2010A, 430A, 430B, 2010B are fed into a pressing element 2020, such that they can overlay each other.

The pressing element 2020 comprises counter rotating rollers 2020A, 2020B which are arranged to guide and press the strips 2010A, 430A, 430B, 2010B which are fed between them.

Downstream of the pressing element 2020 a curing element 2030 acts to part consolidate the strips 2010A, 430A, 430B, 2010B together. The curing element 2030 may be hot air means as described in the above, or may be an ultrasonic means.

The part consolidated strips 2010A, 430A, 430B, 2010B thereafter comprises a lay-up 2300. The lay-up 2300 can be cut to size and processed to form various composite components by known means.

The strips 2010A, 430A, 430B, 2010B can have various fibre orientations, for instance: the strip 2010A comprises two plies which are 90^0 and 0^0; the strip 2010B comprise two plies which are 0^0 and 90^0; the strip 430A comprises two plies which are 45^0 and -45^0; the strip 430B comprises two plies which are -45^0 and 45^0. In this way a lay-up which is [45/-45/90/0]S is given.

It will also be appreciated that this process 2000 can be used to join various numbers of strips together by the provision of additional rolls 2012.

All of the features disclosed in this specification (including any accompanying claims, abstract and drawings), and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at least some of such features and/or steps are mutually exclusive.

Each feature disclosed in this specification (including any accompanying claims, abstract and drawings) may be replaced by alternative features serving the same, equivalent or similar purpose, unless expressly stated otherwise. Thus, unless expressly stated otherwise, each feature disclosed is one example only of a generic series of equivalent or similar features.

The invention is not restricted to the details of the foregoing embodiment(s). The invention extends to any novel one, or any novel combination, of the features disclosed in this specification (including any accompanying claims, abstract and drawings), or to any novel one, or any novel combination, of the steps of any method or process so disclosed.

CLAIMS

1. An apparatus to form off-axis composite material, the apparatus comprising:
   a supply means to operable supply a strip of composite material, the strip comprising a matrix and a plurality of fibres, which are aligned to each other;
   a stationary mandrel arranged to receive a portion of the strip from the supply means, the mandrel and supply means being arranged such that the strip is supplied to the mandrel with the fibres orientated off-axis to an elongate axis of the mandrel,
   a drive means configured to drive the received strip to rotate about the mandrel, and to move axially along the elongate axis of the mandrel such that the strip forms a tube on the mandrel,
   wherein the mandrel is configured to dispense the tube from an end of the mandrel such that the dispensed tube, when pressed into a further strip or sheet, has fibres which have an orientation that is off-axis in relation to the length of the further strip or sheet.

2. The apparatus of claim 1, wherein the strip of composite material is any continuous fibre plastics material or any long fibre plastics material.

3. The apparatus of claim 1, wherein the strip of composite material is a pre-preg strip.

4. The apparatus of any preceding claim, wherein the fibres of the supplied strip of material of the supply means are aligned substantially to the length of the strip.

5. The apparatus of any preceding claim, wherein the angle at which the fibres of the strip of composite material are supplied relative the elongate axis of the mandrel is between 5^0 to 85^0.

6. The apparatus of claim 5, wherein the angle at which the fibres of the strip of composite material are supplied relative the elongate axis of the mandrel is approximately 45^0.

7. The apparatus of any preceding claim, wherein a position of the stationary support is adjustable such that the angle at which the fibres are supplied relative the elongate axis of the mandrel is adjustable, to thereby adjust the angle of the fibres in the further strip dispensed from the mandrel.

8. The apparatus of any preceding claim, wherein the drive means is arranged to engage a surface of the tube on the mandrel.

9. The apparatus of claim 8, wherein the drive means comprises a belt arranged to grip a portion of the tube, such that movement of the belt causes the tube to be moved relative the mandrel by the belt.

10. The apparatus of any preceding claim, wherein the supply means comprises a roll of composite material which is arranged to rotate relative a stationary support.

11. The apparatus of claim 10, wherein the supply means is operatively connected to a second drive means, which is operable to drive the roll to rotate,

wherein the first and second drive means are controlled by a control unit, the control unit configured to actuate both of the first and second drive means to drive simultaneously.

12. The apparatus of any preceding claim, wherein the strip or sheet dispensed from the mandrel comprises two plies, and wherein the angle of the fibres in the first ply relative to a longitudinal axis of the mandrel is equal and opposite to the angle of the fibres in the second ply relative to a longitudinal axis of the mandrel.

13. The apparatus of claim 12, wherein the angle in the first ply is between $5^0 - 85^0$ with respect to a length direction of the elongate axis of the mandrel, and the angle of the fibres in the second ply is between -5^0 to -85^0 with respect to the elongate axis of the mandrel.

14. The apparatus of claim 15, wherein the angle in the first ply is approximately 45^0 with respect to a length direction of the elongate axis of the mandrel, and the angle of the fibres in the second ply is approximately -45^0 with respect to the elongate axis of the mandrel.

15. The apparatus of any preceding claim, wherein the apparatus further comprises a welding element arranged to join a portion of the strip once received on the mandrel to an adjacent portion of strip on the mandrel to thereby form the tube.

16. The apparatus of any preceding claim, wherein an outer surface of the mandrel is substantially cylindrical.

17. The apparatus of any preceding claim, wherein the apparatus further comprises a heating element which is disposed proximate the supply means, which is operable to soften the strip once dispensed from the supply means.

18. The apparatus of any preceding claim, wherein the mandrel comprises a dispensing section for dispensing the tube, and wherein the dispensing section is positioned at a first end of the mandrel, and comprises a tapered section, the taper being arranged such that the diameter of the mandrel is narrower at its tip.

19. The apparatus of claim 18, wherein the apparatus further comprises a receiving means, which is operable to receive the tube once dispensed from the dispensing section of the mandrel, the receiving means comprising a roll which is rotatably mounted to a support structure and rotatable about a rotational axis which is orientated substantially perpendicular to the elongate axis of the mandrel,

wherein the support structure is configured to enable rotation of the roller receiving means about an axis which is substantially aligned to the elongate axis of the mandrel, such that it rotates with the tube to prevent twisting of the tube when dispensed from the dispensing section of the mandrel.

20. The apparatus of claim 19, wherein a cutting element is disposed between the dispensing section of the mandrel and the roller receiving means, which is operable to cut the tube at a first and second point along a line parallel to the axis of rotation of the roller receiving means, wherein the first and second point are diametrically opposed to each other, and

wherein an opening element is disposed between the cutting element and roller receiving means, wherein the opening element comprises guide means, which are configured to guide the cut tube to a substantially flat strip prior to it being received by the receiving means.

21. The apparatus of any of claims 1 to 18, wherein the mandrel comprises a cutting section operable to cut the tube into portions of a given length.

22. The apparatus of claim 21, wherein the cutting section comprises a cutting ring disposed around the mandrel and operable to move along an axis substantially identical to the axis of the tube,

wherein the cutting ring is operable to move between a cutting start position and a cutting end position at a speed substantially identical to the axial motion of the tube whilst performing a cutting operation.

23. The apparatus of claim 22, wherein the cutting ring is operable to return to the cutting start position from the cutting end position whilst performing a return operation, such that the ring-shaped cutting unit is operable to start another cutting operation a fixed distance from the first end of the mandrel.

24. The apparatus of claim 22 or 23, wherein the cutting ring comprises one or more cutter heads, and wherein the cutting ring engages the cutter heads, thereby cutting the tube whilst performing the cutting operation, and wherein the cutting ring disengages the cutter heads whilst performing a return operation.

25. The apparatus of claim 24, wherein the or each cutter head comprises one or more rotatable cutting wheels disposed to cut in a direction substantially transverse to the longitudinal axis of the tube,

wherein the or each rotatable cutting wheel is disposed so that the rotation of the tube forces the or each rotatable cutting wheel into the tube, thereby cutting the tube.

26. The apparatus of any of claims 21 to 25, wherein the apparatus further comprises a flattening section for flattening the portions of tube dispensed by the cutting section, so that a sheet comprising two plies, wherein the angle of the fibres in the first ply is equal and opposite to the angle of the fibres in the second ply, is formed..

27. The apparatus of claim 26, wherein the flattening section comprises a plurality of pairs of rollers, and wherein:

the rollers in each pair are disposed at opposite sides of an elongate axis of the tube,

the rollers are aligned transversely with respect to the axis of the tube,

the rollers in each pair are positioned in the same vertical longitudinal plane, and

the plurality of pairs of rollers are positioned successively from a receiving end, closest to the cutting section, and a dispensing end, furthest from the cutting section, the distance between the rollers in each of the plurality of pairs of rollers decreasing successively from the receiving end to the dispensing end, so that a tube propelled through the flattening section is progressively flattened.

28. The apparatus of claim 26 or 27, wherein the axial motion of the tube propels the tube through the flattening section, forcing the tube to be flattened.

29. The apparatus of any of claims 26 to 28, wherein the apparatus comprises a bonding section, operable to bond together a plurality of sheets of composite material dispensed by the flattening section to form a single multi-ply sheet.

30. The apparatus of claim 29, wherein the plies of the plurality of sheets of composite material are arranged so that the orientation of the fibres in the plies from a top ply to a middle ply is identical to the orientation of the fibres in the plies from a bottom ply to a middle ply.

31. The apparatus of claim 29 or 30, wherein the material is bonded by ultrasonic welding.

32. A method of forming off-axis composite material, the method comprising:

supplying a strip of composite material from a supply means to a stationary mandrel, the strip comprising a matrix and a plurality of fibres, which are aligned to each other, wherein the mandrel and supply means are arranged such that the pre-preg strip is supplied to the mandrel with the fibres orientated off-axis to an elongate axis of the mandrel,

using a drive means to drive the received strip to rotate about the mandrel, and to move axially along the elongate axis of the mandrel such that the pre-preg strip forms a tube on the mandrel;

dispensing the tube from an end of the mandrel such that the dispensed tube when pressed into a strip or sheet has fibres which have an orientation that is off-axis in relation to the length of the strip or sheet.

33. The method of claim 32, wherein prior to supplying the strip to the mandrel, the method includes a step of joining a plurality of strips pre-preg material to form a wider strip of material, the wider strip of material being dispensed by the supply means.

34. The method of claim 35 or 36, wherein the method includes a step of joining a portion of the strip once received on the mandrel to an adjacent portion of strip already on the mandrel by means of a welding element.

35. The method of any of claims 32 to 34, wherein the method includes a step of collecting the dispensed strip as a roll on a receiving means, the roll having an axis of rotation which is oriented substantially perpendicular to the axis of rotation of the mandrel,

wherein the step of collecting the dispensed strip includes a step of rotating the roll about an axis aligned to the elongate axis of the mandrel by means of a rotatable support structure.

36. The method of claim 35, wherein the method further comprises a step of laying one or more further strips with the strip of the roller of the receiving means to form a composite lay-up, the method comprising:

arranging a roll of the or each further strip adjacent a roll from the receiving roller, such that the strip from the receiving roller and the or each further strip when dispensed are laid together when received by a pressing element, the pressing element preferably comprising a plurality of rollers,

wherein the or each further strip comprises strip material arranged with the fibres orientated differently to the fibres of the strip from the receiving roller.

37. The method of any of claims 32 to 34, wherein the method includes a step of cutting the tube into sections using a cutting section.

38. The method of claim 37, wherein the method includes a step of flattening the cut sections of tube to form sheets having fibres which have an orientation that is off-axis in relation to the length of the strip or sheet.

39. The method of claim 38, wherein the method further comprises a step of bonding a plurality of sheets of composite material, the method comprising:
    arranging a plurality of sheets into layers,
    bonding the layers together using ultrasonic welding.

40. The method of claim 39, wherein the plies are arranged so that the orientation of the fibres in the plies from a top ply to a middle ply is identical to the orientation of the fibres in the plies from a bottom ply to a middle ply.

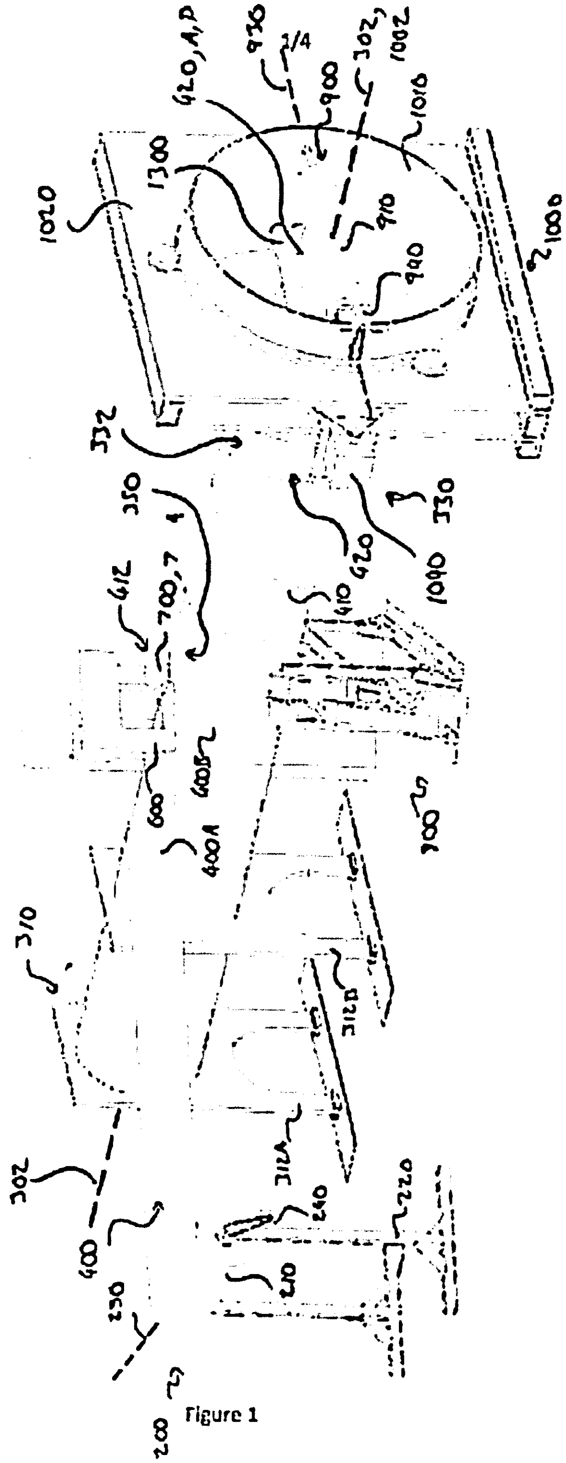


Figure 1

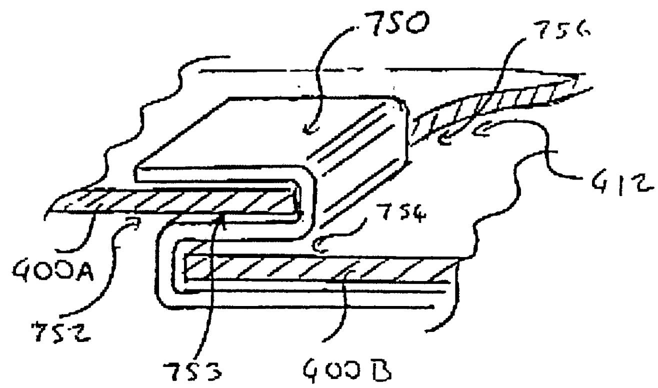


Figure 2

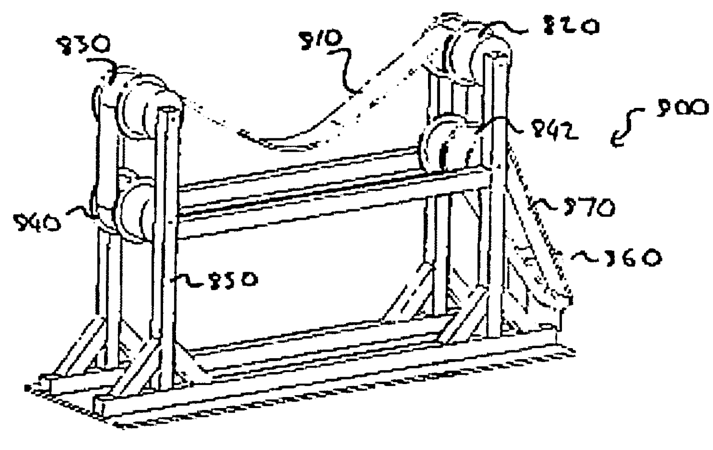


Figure 3

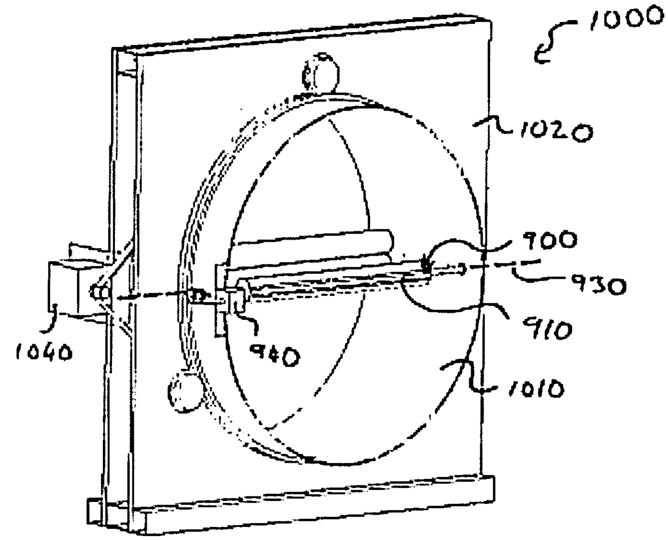


Figure 4

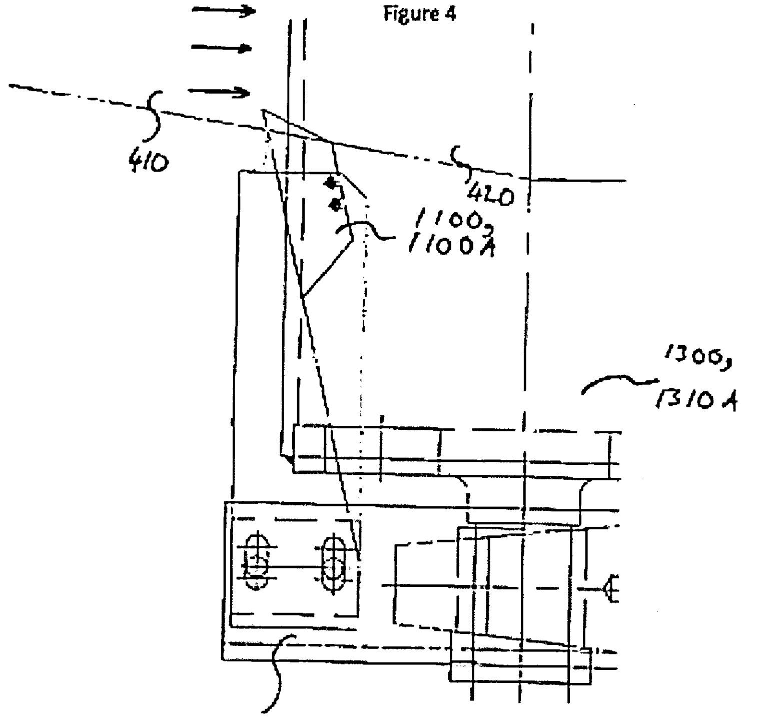


Figure 5

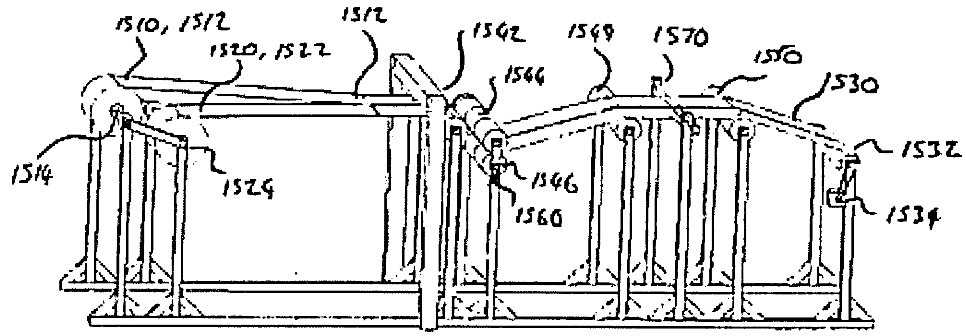


Figure 6

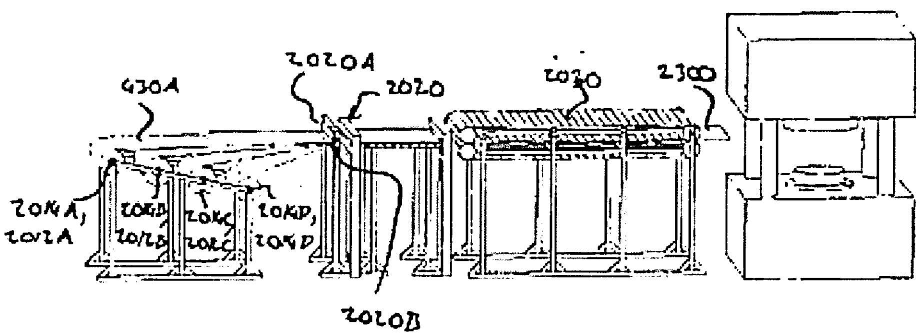


Figure 7

Stage 2 cutter

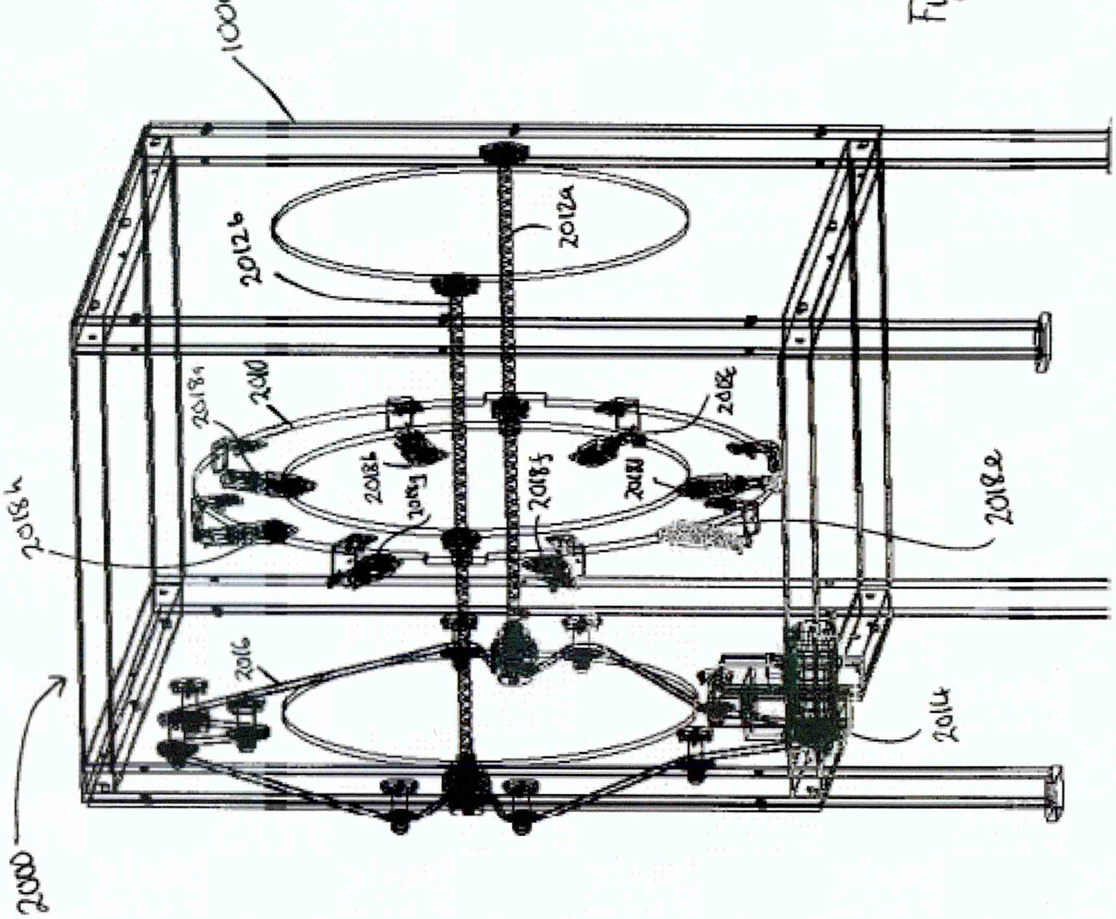
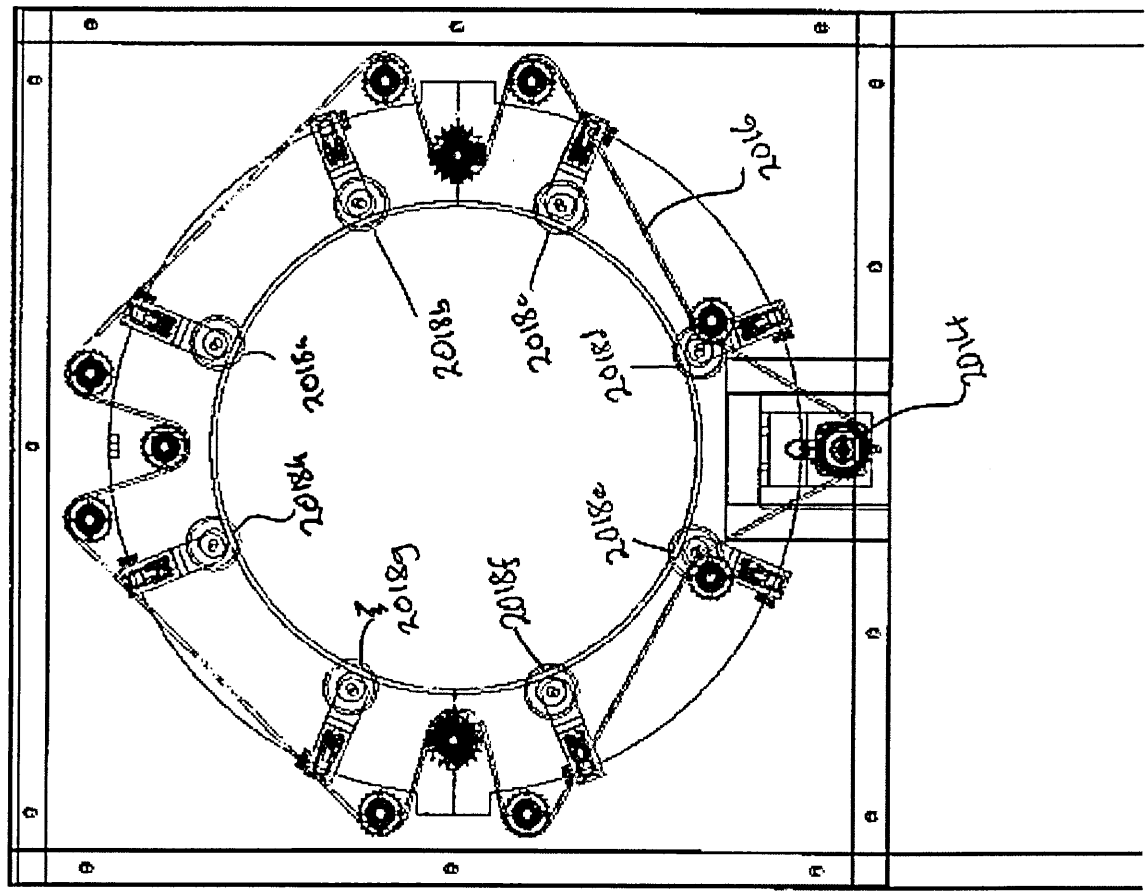


Figure 8

Figure 9



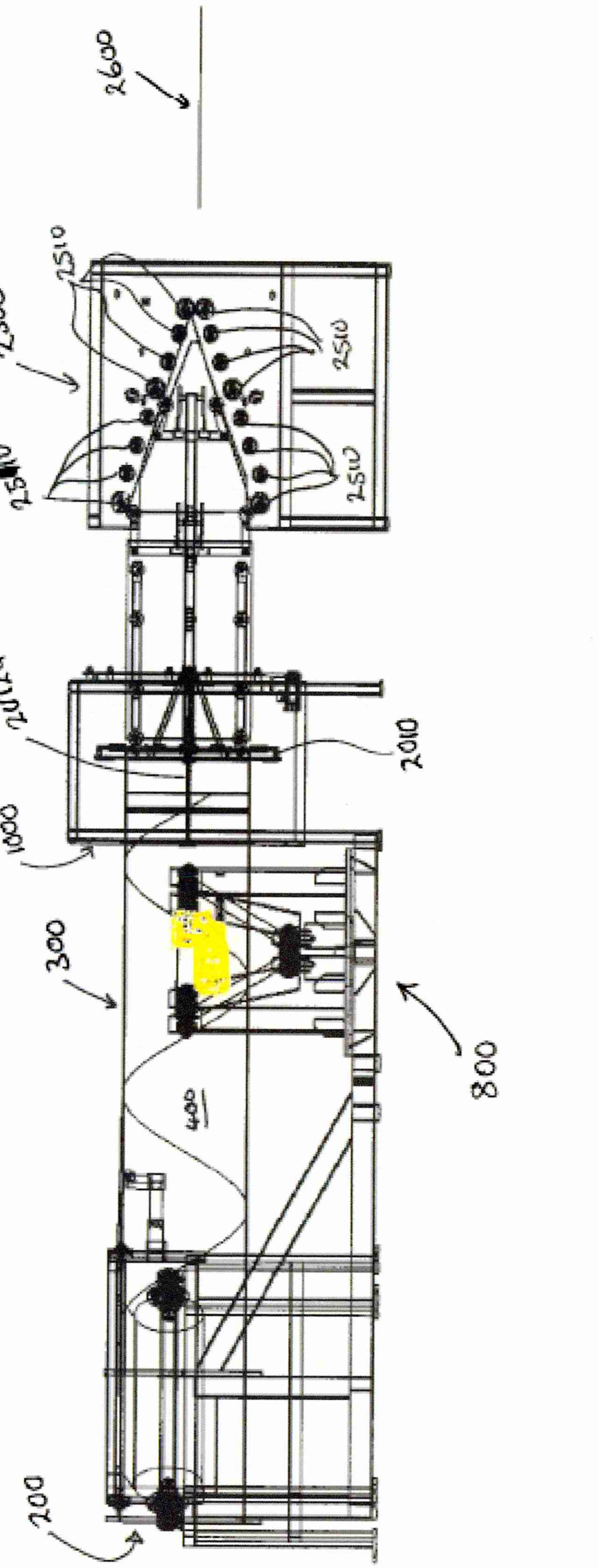


Figure 10