Multifunctional Carbon Fibre Flat Tape for Composites

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List of Abbreviations

DCFP	**Directed Carbon Fibre Preforming**
DFP	**Directed Fibre preforming**
EMI	**Electromagnetic Interference**
FAST	**Fabric Assurance by Simple Testing**
FE	**Finite Element**
FEA	**Finite Element Analysis**
KES	**Kawabata Evaluation System**
MCF	**Metallised Carbon Fibre**
MFCF	**Multifunctional Carbon Fibre**
NCF	**Non-crimp Fabric**
P4	**Programmable Powder Preforming Process**
P4-A	**Programmable Powder Preforming Process for Aerospace**
SEM	**Scanning Electron Microscope**
TP-P4	**Thermoplastic programmable Powder Preforming Process**
UD	**Unidirectional**

Abstract

Recently, there has been a significant growth in the use of composites in sectors such as automotive, aerospace and wind energy. Composites are traditionally designed for mechanical performance in terms of strength, stiffness and impact energy absorption; however multifunctionality has become the focus of researchers and designers in recent years. Multifunctional design of composites involve adding functionality such as thermal management, radiation shielding, stealth, structural health monitoring and energy storage at material level rather than adding discrete components afterwards.

The aim of the current research is to incorporate multi-functionality at tow-scale both as a processing aid during manufacture and adding additional functionality during subsequent processing. Various laboratory scale machines were developed as a part of this study to identify the ideal way to spread and incorporate metallic materials into the carbon fibre tows, thereby making them multifunctional. Manufacturing processes such as co-mingling of micro-fibres, coating with metallic powder and screen printing of metallic grid lines have been developed in this work.

One of the objective of this thesis is to metallise carbon tow in order to use it in conjunction with magnetic tooling, as part of the chopped fibre preforming process developed by the University of Nottingham and Bentley Motors. The performance of the metallised tow has been evaluated using characterisation tests such as magnetic pull force test, bending rigidity test etc. Finite element models have been developed to verify the experimental results of magnetic pull force and bending properties.

As observed during the research, the bending properties of the carbon tow were found to influence the accuracy of the finite element modelling significantly. Study into the bending properties of the carbon fibre and Multifunctional carbon tow using two different principles such as carbon tow bending under own weight and bending due to the application of an external force were carried out. In each case the governing mathematical models were also derived.

Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning;

Copyright Statement

Acknowledgements

I would like to express my sincere gratitude to my supervisor Dr Prasad Potluri for his excellent guidance, patience, motivation, immense knowledge and financial support throughout my MPhil, PhD and research. It has been a pleasure to have been associated with him since (2001) my undergraduate years at the University of Manchester.

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My heart felt gratitude to Bentley Motors for the funding to develop the carbon fibre processing machine from laboratory scale to production scale. Also I would like to thank the NWCC (Northwest Composites Centre), EPSRC (Engineering and Physical Sciences Research Council) and DSTL (Defence Science and Technology Laboratory).

Finally, I would like to thank my family and friends for the continuous support they have given me.

Chapter 1. Introduction

1.1 Background

Traditionally composites are designed for mechanical performance in terms of strength, stiffness and impact energy absorption. Currently an increasing amount of research conducted in this area is focusing on multifunctionality. The conventional approach was to design the composites to satisfy a mechanical performance requirement and other functions separately. Current novel approach is to combine both mechanical functions and other functions together. This has led to the need for developing new materials which fulfil multiple functions in both mechanical and other applications. In addition to mechanical performance (properties such as stiffness, strength and damage tolerance), multi-functional properties for applications such as stealth, electromagnetic interference shielding, de-icing, self-repair, energy storage are being incorporated into composites. In this work, metallised carbon tow has been developed primarily as a processing aid in conjunction with the chopped fibre preforming (DCFP - Directed Carbon Fibre Preforming) process. This tow has the potential for multi-functionality.

In order to use multifunctional carbon fibre for various engineering applications, new manufacturing techniques need to be developed. In the current economics of the world, the cost of manufacturing composites is one of the main concerns of the high volume producer. Addressing this requires both material and process improvements, namely; the use of low cost carbon fibre as well as an efficient and high throughput production process.

1.2 Problem Definition

The uses of carbon fibre composites for structural applications are well established. As mentioned earlier in this chapter, the need for developing new materials that have both structural and non-structural applications that contribute towards weight saving and cost saving is a timely and necessary research gap that needs bridging. Development of a novel material that can replace carbon tow flat tape for composites has the potential to reduce the cost of composites at the same time as improving functionality.

Specifically, in the area of carbon fibre based manufacturing, DCFP is a high speed production process. In this process, chopped carbon fibre and binder are sprayed on to a mould surface, which is then held on to the mould surface using a positive airflow. The present research proposes one such multifunctional carbon fibre material, namely Metallised carbon fibre (MCF) tow, which has the capacity to modify and improve the DFP process. When using this new multifunctional material it has the advantage of removing the necessity for air extraction, thus removing the escape of short fibre and reducing the intermittent mould maintenance required. Another advantage of using the proposed new material is when using spread carbon tow; it increases the fibre volume fraction within the composites. The MCF has multiple other applications such as electromagnetic interference shieling, de-icing/anti-icing, etc. Also when using spread carbon tow for weaving, MCF is capable of reducing the crimp resulting from the weaving process thereby increasing the mechanical properties of the composite.

1.3 Research Aims

The current research is a part of a collaborative research programe carried out in order to create an advanced version of the Directed Carbon Fibre Preforming Process (DCFP), i.e. the production of composite preforms in the presence of a magnetic field. This programe was jointly carried out by the Bentley Motors Ltd and the University of Nottingham. The metallised carbon fibre for the new DCFP process was developed by the University of Manchester.

The research into the creation of metallised carbon fibre (MCF) tape, focuses on the modification of the carbon tow properties, so that it can be handled by electromagnetic tooling during the preforming process. The research conducted has investigated three different approaches to the production of metalized carbon fibre tape with extensive mechanical characterisation of the material to determine the relative superiority of the process and the resulting materials. These approaches are namely:

- deposition of ferromagnetic metal powder;
- commingling metal fibre with the carbon tow;
- printing of a metallic grating.

Mechanical tests were conducted to characterise the new material by varying the quantity of ferromagnetic material. To generate a finite element model of the MCF tow and validate it using experimental results.

1.4 Research Approach

1.4.1 Tow quality parameters considered

There were several parameters which were considered while designing the multi-functional carbon fibre flat tape; they are the epoxy size on the carbon tow, the spread of the tow and finally its metallisation.

Sizing: A water-based epoxy size was added to ensure the cohesiveness of the carbon tows and to bond the magnetic material onto them. The quantity of the size material was maintained up to a maximum value of 1.28% since a further increase of size would lead to higher stiffness. This would prevent the tow from being bent around the mould surface.

Spread: The required tow width is 10-12mm. The spread of carbon tow tends to affect its bending properties. The tow stiffness increases as the spread decreases, and vice versa.

Magnetism: Tow magnetisation was a key aspect of this project. If the carbon tows were less magnetised, the electromagnets that were used to handle them would consume more electricity.

1.4.2 Methods used to metallise the carbon tow:

- Co-mingling with ferromagnetic wires

The cobalt wire can be merged with carbon tow in order to create a metallised carbon tow. This could be carried out in several ways such as by plying or merging in the same direction and epoxy sizing. Practically, plying will not be possible since it can affect the tow spread. Therefore the cobalt wire can be co-mingled with the carbon tow in the same direction using a water-based epoxy size in order to bond the wire within the tow structure.

- Coating with ferromagnetic powder

In this approach, the carbon tape is passed through a size bath which is then spread and powder coated with a fine nickel powder aggregate, which is then cured using infrared heating.

The metallisation principle of this process is to add a continuous layer of nickel powder on top of the carbon tow. A small quantity of size is added in order to stick the nickel powder on to the surface of the carbon tow.

- Line printing of metallic powder

Based on the advantages of the previous two processes, a new process was planned for trial in which nickel powder is mixed with a highly viscous epoxy resin. This paste is then printed on to the surface of the carbon tow so that powder flying off the surface can be stopped and a homogeneous metallisation can be achieved. . The resulting metalized tape is heat cured which is subsequently cooled in to the final metalized tape before flat winding on to bobbins.

The prototype machine that needs to be built in order to manufacture the above MCF tape will consist of six manufacturing process zones which include (i) let off zone, (ii) sizing zone, (iii) spreading zone, (iv) printing zone, (v) drying zone, (vi) cooling zone and (vii) winding zone.

1.4.3 Mechanical testing and finite element analysis

MCF produced using various methods were characterised by changing the process parameters like size concentration, ferromagnetic materials etc. Magnetic pull force vs. air gap of the MCF was tested and the results of the test were validate using ANSYS finite element analysis package. The bending properties of the MCF were measured using various techniques like cantilever, three point and Kawabata testing, finally the results were compared.

1.5 Thesis layout

A literature review of the earlier work in the area of multifunctional carbon fibres is carried out in chapter 2. Since this research is specifically applied to the spread carbon fibre coated with metal, it initially provides a publication review of an overview of its multifunctional applications. These include a review of anti/de-icing, EMI shielding, spread carbon tow benefits and aids to preforming. Literature on the composite material used in the automotive sector was also discussed and finally literature about the carbon fibres that are currently available in the market coated with metals are reviewed.

Chapter 3 is a report on the development of the prototype machines used to metallise the carbon tow. The work presented in this chapter includes coating with ferromagnetic powder, co-mingling with fine ferromagnetic wires and final printing carried out in the form of a metallic grating. The principles of each process were also discussed.

In chapter 4 the influence of printing metal powder intermittently on the carbon tow was studied. This includes changing the position of single magnetic print lines under a magnetic field created by a single cylindrical magnet and the resultant magnetic pull force was measured. A Finite Element Analysis (FEA) model for the same was also generated and the results were compared. Further study was conducted by changing the position of several print lines under an array of magnets. This study was conducted by changing its position under the magnet and by varying the distance between the magnets and print lines. Also a FEA of both the cases was also performed to validate the results. Finally the bending properties of MCF tow under the influence of an array of magnets was also studied and a finite element model was created.

The effect of changing the quantity of metal content in the print lines is discussed in chapter 5. A series of magnetic pull force tests was carried out by varying the distance between the print line, the quantity of metal in the print lines and finally by varying the width of each print line. Further characterisation of the bending stiffness of the MCF tow was also carried out.

Chapter 6 investigates further into the process development and material characterisation of the co-mingled carbon fibre and cobalt wire. Bending stiffness of the co-mingled carbon tow was studied by varying the epoxy size concentration. A magnetic pull force study was conducted by varying the number of cobalt wires in the carbon tow. Further research into the magnetic pull force was performed by varying the distance between the magnet and the co-mingled tow. A Finite Element model of the co-mingled tow was also created.

In chapter 7, the bending stiffness of carbon tow coated with metal was studied in detail, as it is a major input parameter in the modelling software used for simulating carbon composites[1]. These include investigation of bending stiffness resulting from different modes of material bending such as bending the tow under its own weight and by application of external force. These tests were conducted using cantilever, Kawabata, 3 point and finally 2 point bending methods. Mathematical models that characterise the behaviour of carbon tow in each of these cases were also presented in this chapter.

Chapter 8 summarises the conclusions made in each of the previous chapters written in order to present the work carried out to develop the prototype MCF tow printing machine and the characterisation of the MCF tow manufactured using the same prototype machines. It further presents the future investigations that can be carried out.

1.6 Summary

In chapter 1, the background of multifunctional carbon tow was briefly discussed, followed by the need for metal coated carbon fibre. This chapter presents the aims of the thesis in order to address the research gap in multifunctional carbon fibre material for manufacturing applications. Further it also presents the scope of the research in addressing the research gap. The thesis layout of each chapter was also included in Chapter 1. The chapters 4, 5, 6 and 7 are written with a view of publication in renowned international journals.

Chapter 2. Literature review

In this chapter, literature on the functionalisation of carbon tow is discussed, followed by the applications of metal coated spread carbon tow as a multifunctional material. Multifunctional applications like electromagnetic interference shielding, anti-icing, de-icing and the benefits of spread tow are also discussed. The potential for composites in the automotive industry are studied. Different techniques of chopped fibre preforming process are also analysed and finally an electroplated metalcoated carbon fibre process currently available in the market is also described.

The use of carbon fibre in composites has gained significant importance in a wide range of applications, such as wind energy, pressure vessels, aerospace, defence, automotive, sporting equipment, off-shore oil and gas applications etc. This is due to the characteristics of carbon fibre, including stiffness, tensile strength, light weight, chemical resistance, temperature tolerance etc. The global demand for carbon fibre in 2012 was 67,000 MT and is expected to reach 141,000 MT by 2020. The carbon fibre industry is expected to grow 11.9% annually, with 6.4 billion GBP in 2012 to 15.4 billion GBP by 2020[2].

Carbon fibre composite materials are traditionally used for load bearing and weight saving applications. Currently, carbon fibre composites are used for structural and non-structural applications, such as electrical conduction, sensing, electromagnetic shielding and heating. [3].

2.1 Carbon tow functionalisation

Multifunctional carbon fibre composites [MFCF] have more than one function other than structural applications. Some sub-applications of the MFCF composites are de-icing, anti-icing, electromagnetic interference shielding, online health monitoring, energy storage etc. [4] This is driven by the degree of material utilisation and energy efficiency.

Depending on the application MFCF can offer several benefits when it is designed, analysed and by incorporating different functions. **Table 2-1** shows the MFCF and its integral application according to Lockheed Martin astronautics, Denver. [5]

MFCF	Functions
Metal matrix composites	structural, thermal, electrical grounding
Intercalated Gr/epoxy	structural, thermal, electrical grounding
Structural electronics	structural, electrical
Carbon-carbon	structural, thermal shielding, antenna
Multiphase composites	multifunctional distributed phases

Table 2-1 Multifunctional carbon fibre composite and its functions [5]

In the last decade there were several advancements in the area of fibres, innovative preforming processes, smart materials, sensors. The future of composites in the aircraft and automotive industries depends on the need for a reduction in weight/volume in comparison to current designs and the conventional approach is to replace metal parts with composite structures. By incorporating sub-functions into composites, and thus adding to their functionality, will add to the benefits of using composites instead of metals.

Adding metal to the carbon fibre has several sub-function advantages, like EMI shielding, anti-icing and de-icing etc., without compromising the advantages of using carbon fibre, such as weight saving, tensile properties etc.

2.2 Applications of multifunctional metal coated composites

There are various applications of multi-functional carbon tow, such as electromagnetic interference shielding and anti-icing, de-icing etc.

2.2.1 Electromagnetic interference shielding

The reflection and / or absorption of electromagnetic radiation by a material are referred to as electromagnetic interference shielding, which acts as a shield against the penetration of radiation [6]. Electronic devices with increasing complexity in terms of high packing density for faster response have resulted in a need for electromagnetic interference [7]. Many radiated signals in EMI cause degradation of the system and affect its performance [8]. One of the most common causes of EMI is electrostatic discharge. Electronic devices can be prevented from malfunctioning by shielding them from incoming and outgoing interference filter. Rapid growth of radio frequency electronics in today's society has increased the importance of EMI shielding [9-16].

Absorption and reflection takes place when electromagnetic waves pass through a shield. Reflection is usually the primary mechanism of EMI shielding. The shields with mobile charge carriers, like electrons or holes which interact with the electromagnetic fields in the radiation, are necessary for the reflection of radiation by the shield. This results in electric conduction in the shield. Conduction requires connectivity in the conduction path; therefore, shielding is enhanced by connectivity [6]. For absorption to take place the shield should have an electric and / or magnetic dipole which can interact with the electromagnetic field in the radiation.

Multiple reflections is another function of the shielding, this is referred to as reflection by various surfaces in the shield. The product of σ_r and μ_r is absorption loss and reflection loss as a function of the ratio σ_r / μ_r. Where σ_r is relative magnetic permeability and μ_r is the electrical conductivity relative to copper.

The ratio of impinging energy to residual energy is called the shielding effectiveness (SE). The three mechanisms absorption (A), reflection (R) and multiple reflections (B), which cause attenuation of electromagnetic waves, are shown in **Figure 2-1** i.e. SE= A+R+B [17].

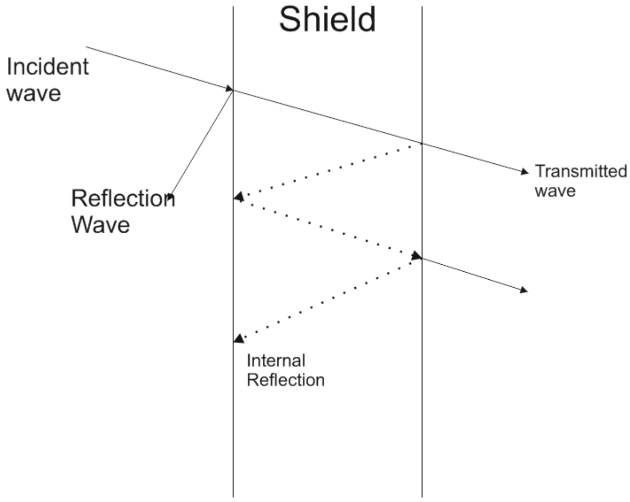

Figure 2-1 Shielding effectiveness

The most common material used for EMI shielding is metals. Highly conductive materials like silver, gold, aluminium are excellent for reflection. Free electrons in the metals function mainly as reflection for shielding purposes. Metal coating by electroplating, electrode less plating or vacuum deposition are used in shielding as metal sheets are bulky [6], Coating can be done on materials like bulk metal, fibres, particles etc. but coating can suffer from scratches.

The skin effect is when electromagnetic radiation with high frequency penetrates to the surface of the electrical conductor. The plane wave of an electric field drops significantly as it penetrates into the depth of the conductor [6]. The incident value skin depth (δ) is the depth at which the field drops to 1/e.

where: $\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$

f = frequency,

μ= magnetic permeability, which is $\mu_0\mu_r$, where μ_r is relative permeability, μ_0 is the permeability of free space, $4\pi \times 10^{-7}$ Hm^{-1}

σ= electric conductivity $\Omega^{-1}m^{-1}$

Due to the ferromagnetic nature of nickel, it has a low skin depth value compared to that of copper. Composites with conductive filler of small unit size are more effective than high unit size due to the skin effect. The ease of processing has led to polymer–matrix containing conductive fillers to be attractive for shielding. Even though electric conductive resins are increasingly available they are hard to process, but electrically conductive resin does not need conductive fillers for shielding. The advantage of using conductive fillers and electrically conductive polymers is that the polymer can connect fillers that are not touching each other and, therefore, enhance the connectivity [6].

In general, composites with low proportions of fillers are desirable for EMI shielding; this is because the fillers tend to reduce the strength of the composites due to poor bonding between the filler and the matrix. For an effective conductive filler it is preferred to have a smaller unit size relative to skin depth. Also, a high conductivity for reflection by the shield and a high aspect ratio for connectivity are preferable. Due to the above mentioned reasons, a high aspect ratio fibre is preferred, rather than particles.

Short carbon fibres are used in EMI shielding [18] because of the small diameter and catalytically grown carbon fibre (0.1um), which is more effective than conventional short carbon for EMI shielding at the same fibre volume fraction [19, 20]. Comparing thermoplastic carbon filaments/fibres with volume fraction 19% and 20% gives an effective shielding of 74dB and 46dB at 1GHz respectively [21, 22].

Metal fibres are more attractive than carbon fibres for EMI shielding due to their higher conductivity. Electro-coating nickel on to filaments has proven effective [20, 22, 23]. Carbon fibre filament which is coated with nickel is commonly known as nickel filament because of the high nickel content rather than carbon. Nickel filament composite with a fibre volume fraction of 7% has an effective shielding of 87dB at 1Gz [24]. Nickel is also proven to be better than copper because of its oxidising resistance, as oxidising film is poor in conductivity.

When comparing discontinuous fibre with continuous fibres for EMI shielding, discontinuous fibre is preferred for non-structural composites and continuous fibres for structural composites for EMI shielding in aircraft and electronic enclosures. Continuous carbon fibre which is coated with nickel using electroplating to increase conductivity is preferred [6, 21, 22, 25, 26].

2.2.2 Heating for anti-icing and de-icing

Multifunctional composite materials could be used for anti-icing and de-icing in aircraft and wind turbines.

2.2.2.1 Aircraft

Various meteorological phenomena can result in ice formation on a plane (**Figure 2-2**), on the aerodynamic structures that can affect the flight by increasing energy consumption, air resistance, lift, weight and reduced lift. Even an ice layer as thin as 1mm on the wing surface can affect the aerodynamic lift and destabilise a flight [27].

In conventional aluminium wings de-icing is generally referred to as high energy consuming and ice melts slowly due to thermal diffusion. Composites are increasingly being used on aircraft recently for weight reduction, which leads to better fuel efficiency. The thermal conductivity of composites is poor compared to that of metals. There are several cases of UAV crashes due to icing [28]. To address this issue various research has been done on heating of composites for icing [29, 30].

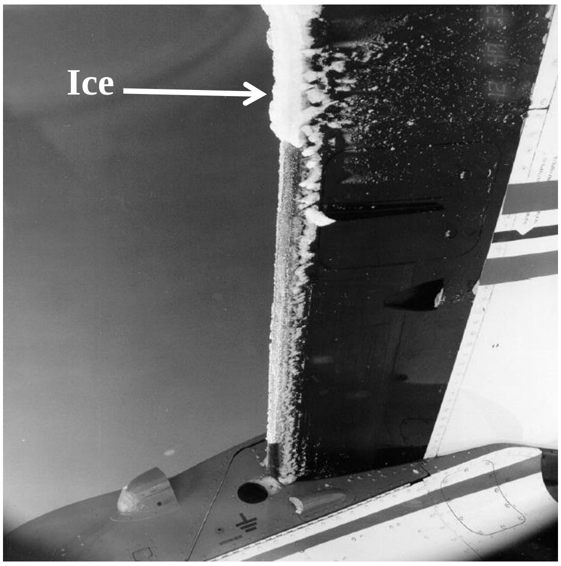

Figure 2-2 Icing that could not be removed by pneumatic boots [29]

There are two forms of icing treatment, which are anti-icing (ice prevention) and de-icing (ice elimination). Anti-icing is referred to as a continuously working system which prevents the ice formation by a pre-heated surface; and de-icing is referred to as a cyclic working system which is used to remove the ice from the surface.

There are several methods for anti-/de-icing which are conventionally used in aircraft currently:

- hot air taken from the engine and transferred to the aircraft parts and systems;
- de-icing liquid transferred to the aircraft parts;
- electric heating of iced parts by ohmic heating;
- ice is removed using pneumatic systems / inflatable boots.

Pilots generally prefer a continuously working anti-icing system [31]. Super-cooled large droplets of water tend to remain in liquid state even at -40 ^{0}C temperature [32]. The highest risk of ice formation on a plane is between a temperature of 0 to -10 ^{0}C at an altitude of ~7000m [30].

Availability of hot air is limited in turbo powered aircraft so mechanical systems, like pneumatic systems, are used but this system is considered inefficient and unreliable as icing water may enter the boot and cause a malfunction [30]. De-icing systems can also rely on chemical application before take-off. One of the preferred technologies to de-ice is to incorporate the heating element under the wing skin to heat directly. There are design challenges to this, such as to develop an even heating element or foil to distribute heat evenly.

GKN Aerospace has developed the icing system for the Boeing 787 commercial aircraft and the V-22 and F-35 military aircraft. Spray mat metal deposition technology was used as liquid metal sprayed onto a mat, which provides conductivity for heating. According to GKN Aerospace this technology can be embedded into the carbon fibre composite structure which was used on the 787. In this icing system, a 15 ply layup begins with a ply stack of carbon fibre and epoxy prepreg, which is either woven or unidirectional. The prepreg is woven on the 787 heater mat. The de-icing mat used in the Boeing 787 can have a temperature variation from 7.2 to 21.1 ^{0}C and a power consumption of 45 to 75 kW. The anti-icing system power varies from 150 to 200 kW depending on the size of the aircraft. This system could be further developed for a sensor-based structural health monitoring system to check the load, detect cracking, detect stresses, breaks and other material flows which are hard to detect [27].

2.2.2.2 Wind turbines

The operation of wind turbines, which operate in very cold temperatures and at high altitudes, often faces the problem of icing as shown on **Figure 2-3** [33]. Offshore wind turbines also face the problem of cold climates, like sea ice and atmospheric icing [34]. High altitude conditions have a wind speed of 0.1 m/s per 100m altitude for the first 1000m and in cold regions generally there is 10% more [35].

This icing could create several problems, such as power losses, mechanical problems (stoppage, aerodynamic disruption, overload due to stall, and decreased fatigue), electric failure, safety concern and measurement error in the control system [36, 37].

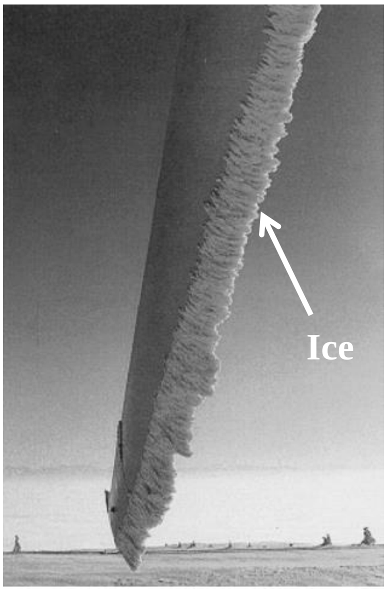

Figure 2-3 Ice on wind turbine blade [38]

There are several systems of existing ice prevention and mitigation, such as an active heating system which is used widely, and hydrophobic coating. An alternative method of providing a heating system is by coating the material with metal and heating it.

2.3 Spread carbon tow

Spread carbon tow has a number of advantages, such as relatively lower crimp, improved wetting ability, toughness etc. Also spreading a carbon tow of higher count like 12K has several advantages, like improved drapability, mechanical properties and weight reduction of 20-30% composite materials. Fabrics of low area density are generally produced using carbon tow of lower counts, like 1K to 6K, which are also costly compared to that of 12K. The 12K carbon is spread so it can be used instead of lower count carbon fibre, especially in the case of automotive composites to reduce cost [39]. **Figure 2-4** shows the difference between spread and unspread tow [40].

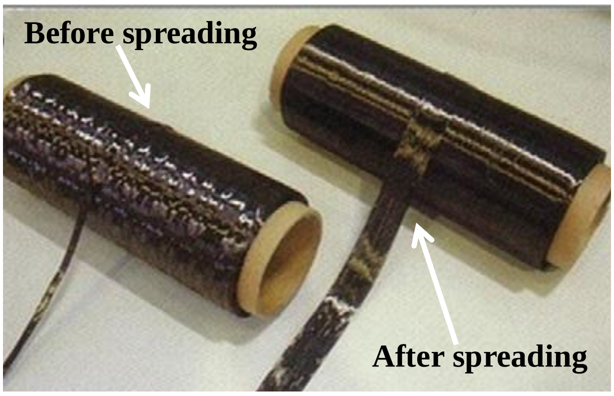

Figure 2-4 12K carbon tow before and after spreading [40]

In the case of spread tow woven fabric as seen in **Figure 2-5**, the ability to take more tensile and compressive loading is increased due to the fibre orientation, which is straightest in both in plane and out of plane. This fabric behaves mechanically similarly to that of unidirectional fabric (UD). Another advantage of spreading carbon tow is that it increases the fibre volume fraction. It also has fewer interaction points, thus, reducing the crimp frequency and angle. When the interaction points are reduced this also reduces the air gap or opening. The reduction in interaction points also increases the mechanical properties [41]. Another advantage of using spread carbon tow is that it is thinner and it has more surface area compared to that of unspread tow, which leads to improved wetting of fibres during infusion of resin.

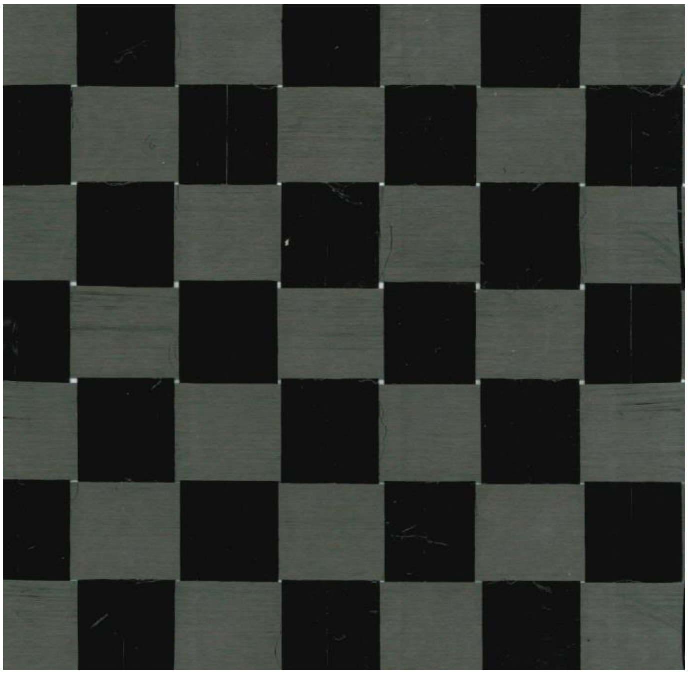

Figure 2-5 Woven fabric using spread carbon tow.

In the case of UD (Unidirectional), non-crimp fabric (NCF) and woven fabric made using the spread tow the drapability of the preform is also increased compared to that of unspread tow. The key advantage of UD fabric is that it drapes easily on moulded surfaces and the disadvantage of it is that it wrinkles and splits on complex shapes creating uneven distribution. NCF fabrics are not as drapable compared to that of UD fabric. This is due to fibres in different orientations being held together by stitches, which restrict the movement of fibres and limited their ability to assume the complex shapes of the mould surface. When using woven fabric the drapability of the woven fabric is increased but mechanical properties get lowered due to crimp [39]. This reduction in mechanical properties can be reduced by either low count carbon fibre or by using spread carbon tow for weaving. Also the crimp depends on weave structure, such as plain, twill, satins etc.

According to Tsai, thin-ply laminated compaosites can supress delamination and micro cracking[42]. Conventional homogenous materials like aluminium and steel are designed to fit the product properties whereas in the case of composites, design is in accordance to the needs of the material structural properties. Composite preforms can be systematically engineered for a particular application and reduced weight. Spread carbon tow of higher count is cost effective for high volume markets like the automotive industry instead of using lower count carbon fibres.

2.4 Automotive composites market growth

This section gives an overview of automotive composites, reflecting on cost, weight saving and market size.

Automotive manufacturers are looking for ways to reduce emissions due to regulations and consumers demanding efficient vehicles because of the increasing fuel cost and emissions taxes. The challenge faced by automobile manufacturers is the balance between environmentally friendly cars and the price expected by the consumer. One of the ways to reduce emissions is by decreasing the overall weight of the car by using lightweight composites to replace metal parts, without a considerable increase in manufacturing cost. The cost of composites is a major concern for automotive manufacturers.

2.4.1 Weight saving

Overall weight of the automobile is directly related to the quantity of the fuel it consumes. Reduction in the weight of the car by 20% increases the fuel efficiency by 8.4% [43]. Original equipment manufacturers in the automotive industry are facing a strict government mandate to reduce fuel consumption, thus, reducing emissions [44].

The Kyoto protocol, passed by some countries, is widely accepted as the underlying global standard for a commitment to reduce CO_2. The Kyoto protocol came into force on 16 February 2005 with a legally binding reduction of greenhouse gas emissions of an average of 5% below 1990 levels in the years 2008-2012 [45]. Further reduction of emissions of 18% below 1990 levels between the years 2013-2020 was committed to by the parties of the Kyoto protocol at the 2012 Doha climate change talks [46]. To meet the protocol targets there is considerable pressure on the automotive manufacturers by governments to reduce fuel consumption, as it is directly linked to the weight of the car [47]. It is possible to reduce the weight of components by 50-70% by replacing metallic materials with composites [48].

2.4.2 Cost of composites

The cost of the composites is one of the major concerns of automobile manufacturers. To reduce the cost of the composites requires low cost carbon fibres as well as high throughput production processes. Pure carbon fibre is 15 times more expensive than steel [49].

Cost structure of manufacturing composites		
	Simple/ Large part (%)	**Complex/ Complex part (%)**
Carbon fibre	20	13
Resin	5	2
Prepreg preparation	10	8
Fabrication and tooling	35	57
Finishing and assembly	30	20

Table 2-2 Cost structure of manufacturing composites [50]

To manufacture a simple part 65% of the total cost is for the fabrication/tooling and the finishing assembly. In the case of complex parts, 75% of the total cost of the composites is attributed to the fabrication/tooling and the finishing assembly (Table 2-2). Market research by Frost & Sullivan has predicted that the price of carbon fibre will decrease from £212/kg in 1970 to £9/kg in 2020 [50].

2.4.3 Automotive industry market size and carbon fibre usage

By 2020, it is expected that there will be about 1.2 billion automobiles on the road and over 110 million automobiles are expected to be sold that year alone [51]. The use of carbon fibre composites in the automotive industry is expected to grow from 8.9 million GBP in 2012 to 58 million GBP in 2017 [50]. To meet the demand of carbon fibre composites in the automotive industry, a high throughput preforming process like chopped fibre preforming is required.

2.5 Chopped carbon fibre preforming

Composites consist of two parts: fibre reinforcement and matrix. The fibre reinforcement which is formed before the moulding process is called a preform. This perform can be a one dimensional linear assembly of filaments, two dimensional like chopped fibres, weaving, braiding, knitting; weaving and braiding could produce a 3D preform. Chopped fibre is one of the fastest preforming processes with up to 20 kg/min [52] according to research by Oak Ridge National Laboratory (ORNL) and the Automotive Composites Consortium (ACC - a partnership of Daimler Chrysler, Ford and General motors [53]).

There are a number of technological developments of the chopped carbon fibre that have taken place since its introduction that have led to the establishment of DCFP the directed carbon fibre preforming process.

2.5.1 Different types of chopped carbon fibre process

Chopped fibre preform composites are developed to bridge the gap between the low performance SMC and high cost/high performance pre-impregnates. It has the advantage of forming complex 3D shapes, near net shapes, high throughput. [54]. The chopped carbon fibre process is economically feasible for medium volumes (1000-20,000 ppa). It also offers a weight reduction of 50% compared to that of aluminium [55].

The work on chopped fibre preforming started in the 1950s with the availability of continuous strand roving and by the 1960s, work on short fibre composites for the aerospace industry had started [56-59]. The window frames of the Boeing 787 Dreamliner use HexMC® which is a chopped carbon fibre composite [60, 61]. Examples of chopped fibre preform composites can be seen in **Figure 2-6** [54].

Figure 2-6 Examples of composites made using chopped fibre preform process [54]

There are various names for chopped fibre preforming for composites, each having small differences in different stages of the process.

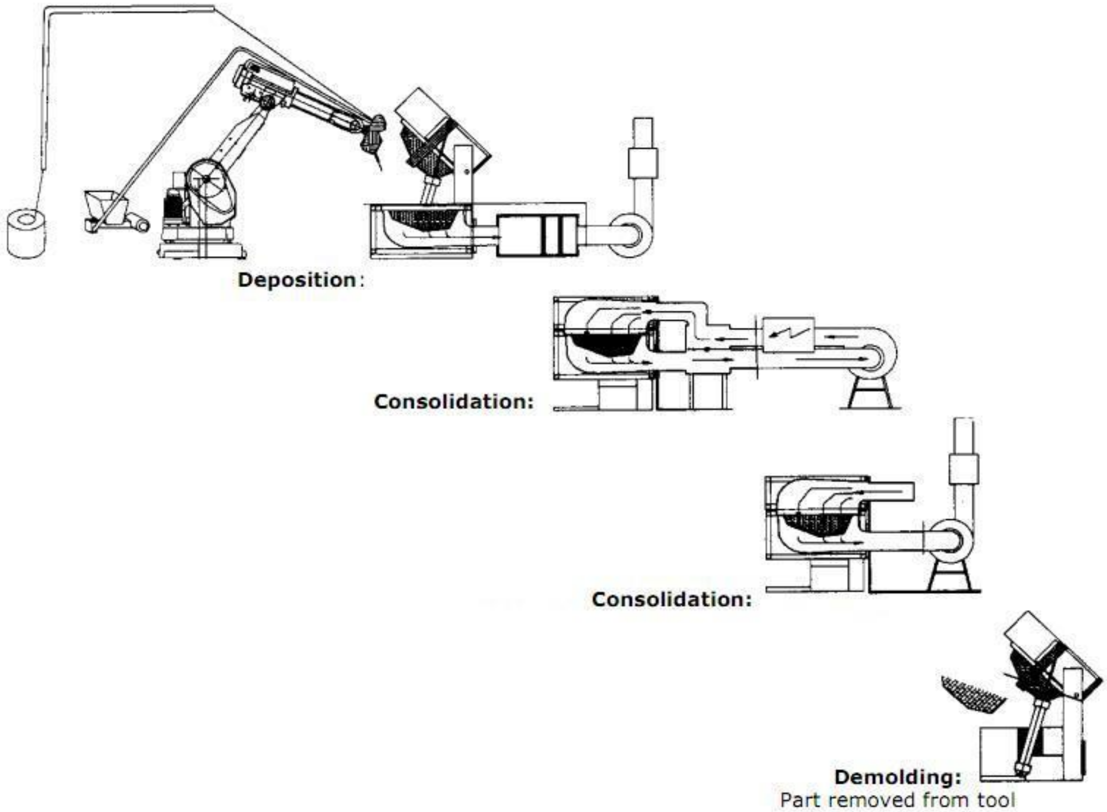

Figure 2-7 P4 chopped fibre preforming process [62]

Owens Corning together with Applicator Systems of Sweden have developed the Programmable Powdered Preform Process or P4 (**Figure 2-7**). In this process chopped fibre and a binder are sprayed onto a mould surface, which is then heat cured using hot air to set the binder. This is followed by consolidation at room temperature and finally the moulds are taken out. P4 technology has the advantage of consistency, control of fibre placement/orientation, producing complex mould geometry, as well as low waste and cycle time [56]. A modified version of P4 developed for aerospace is P4-A. Carbon and glass preforms that were produced after analysing the laminate strength and properties concluded that P-4A was a viable candidate for most aerospace structures.

The laminate strength of this process composites approach 70-80% of continuous fibre laminate strength [63, 64]. The TP-P4 (thermoplastic programmable powdered preforming process) uses chopped glass/polypropylene commingled yarn which is chopped and deposited on to a mould using a vacuum and heat set. The typical cycle time was 40s for a 0.5 x 0.5 m^2 sample weight 2kg [65]. The US Air Force Research Laboratory (AFRL) also had initiated projects to demonstrate the feasibility of adapting the P4 technology for cost effective aerospace composites [64]. P4A was funded by AFRL and NCC was the prime lead with several industrial partners like Boeing Seattle, Boeing St. Louis, Lockheed Martin Aeronautical systems, Northrop Grumman and the University of Dayton Research Institute [66].

The flame spray process was developed by Dow [56]; in this process a spray of hot melt thermoplastic binder together with chopped fibre is sprayed onto a mould surface. The binder cures immediately on contact with the fibre which in turn removes other steps like setting and curing. There are other versions of chopped fibre preforming process like the advanced preforming process (APP) by MFG.

The National Composites Centre (NCC Kettering, OH) has designed a modified version of the P4, which is called Directed Fibre Preform (DFP) technology. In the Directed Fibre Preforming process (DFP) a stream of chopped fibre and binder is sprayed onto a mould surface. Finally, both fibre and binder are consolidated to deliver a consistent preform shape of a high quality. The preform is then infused by a liquid moulding process [56].

A modified version of the Directed Carbon Fibre Preforming Process, called the RayCell project, is a discontinuous carbon fibre manufacturing technique which was jointly developed by Bentley Motors Limited and the University of Nottingham. In this process chopped carbon fibre and epoxy powder are sprayed on to a mould surface to create a near net shape preform. The fibres are cut using a chopper gun with a rotating blade; a propane burner at the end of the nozzle mixes the carbon tow and epoxy, and the powder is activated by the burner. The epoxy is solidified rapidly on contact with the mould surface. An 8mm anti-static hose delivers the powder to the burner [55].

The challenges which are faced by chopped fibre preforms processes are to manufacture thick-section and deep-draw parts [55]. This is due to the limit in the amount of fibres, which can be held in position with a vacuum, which causes the fibre to fall off the edges. The use of the compression moulding technique eliminates the preform consolidation, cooling and transfer; this also reduces the process cost.

Compared to steel, the relative mass saving is 50-70% when using chopped carbon fibre reinforced composites [53]. Studies on manufacturing cost have shown that below 500 parts/annum semi-prepreg is cheaper and chopped fibre offers low cost from 500-9000 parts/annum above 9000 parts/annum steel components were seen to be more cost effective [67].

2.6 Metal Coated Carbon Fibre

Carbon fibre can be coated with nickel powder using an electrochemical deposition or electrolysis process, sol-gel, chemical vapour deposition [68]. This material has a high-performance with the material characteristics of carbon fibre and the electric properties of metal. The material is mainly used for EMI electromagnetic interference shielding filters [69] and ESD electrostatic dissipation. These technologies are of importance to various industrial sectors like the automotive, cell-phone, laptop computer and military markets [70]. The weight increase of the carbon fibre which is currently available in the market has increased due to the nickel powder coating by up to 81% [69]. Linear resistivity varies from 79 Ω/m from 15% Ni on 3K to 0.33 Ω/m for 50% Ni on 50K [71]. SEM images of electroless nickel coated carbon fibre can be seen in **Figure 2-8**.

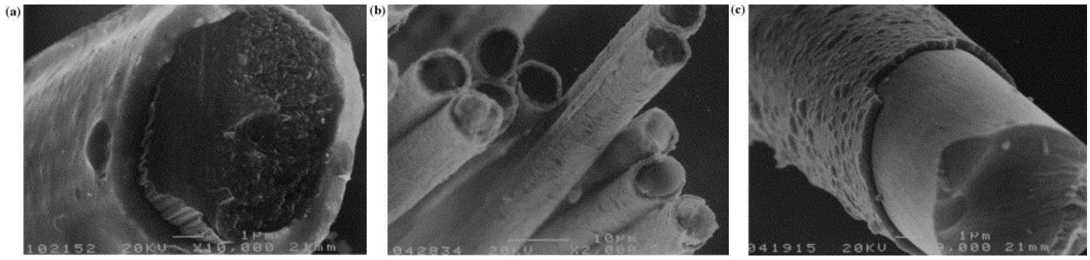

Figure 2-8 SEM image of electro less nickel-coated carbon fibres [72].

Electro deposition of nickel on a single tow of 12k carbon fibre developed by B. Pierozynski [70] consists of five sections as shown in **Figure 2-9**: let-off or fibre pay-out assembly (1). An electroplating unit is made with PVC (2), rinsing station (3), fibre drying (4) and winding zone/spool take up assembly (5). Details of electroplating units are presented in **Figure 2-10**.

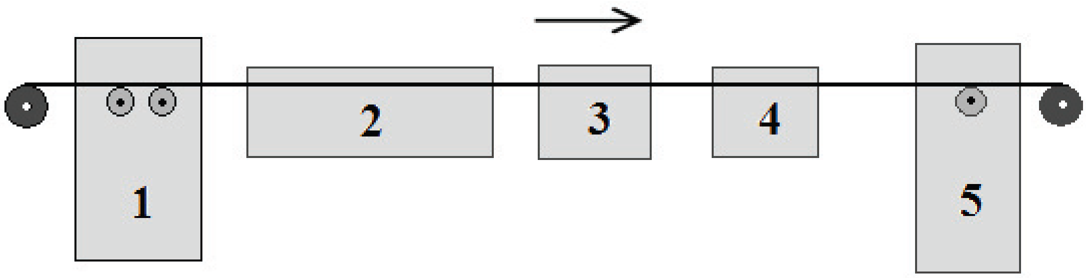

Figure 2-9 let-off (1), Electroplating unit made with PVC (2), rinsing station (3), drying (4) and winding zone (5) [70]

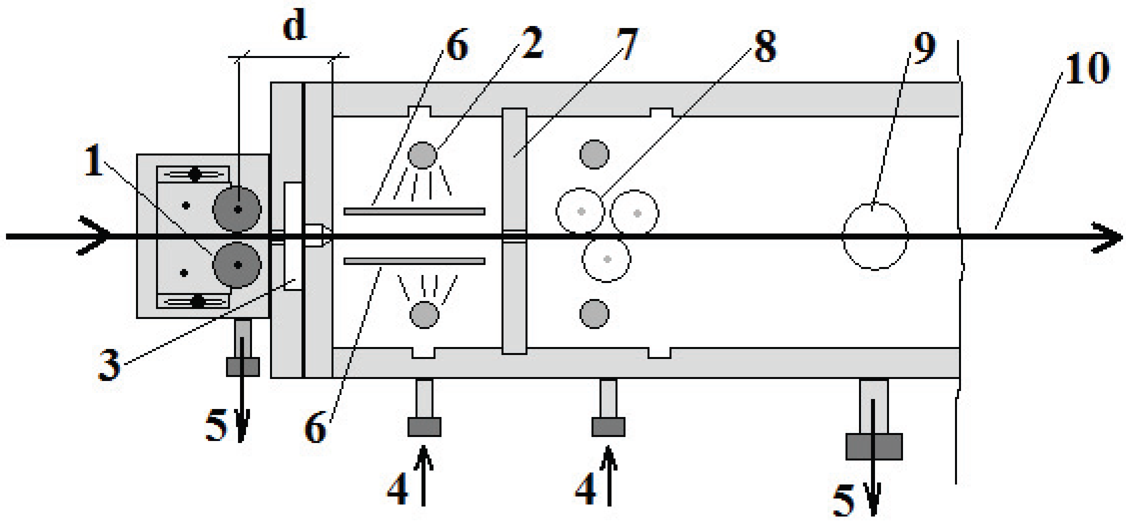

Figure 2-10 The electroplating unit consists of CR assembly (1), electrolyte sprinkler (2), electrical over unit (3), electrolyte circulation in (4), electrolyte circulation out (5), anode(6), adjustable wall (7), adjustable warp type cathodic CR assembly mounted on the electroplater cover (8), Draining electrolyte (9) and carbon fibre passage (10) [70]

The quality of nickel coated carbon fibre made using this technique depends mainly on the extent of carbon fibre tow spreading within the electroplaters. In this process it was assumed that all the filaments of 12k are spread and are in contact with the cathode rollers (CR). The filaments, which are not in contact, will have to overcome the radial resistivity of the fibres that shield it from the cathode rollers. Fibres which are not in contact with the rollers have less current density compared to that of fibres which are in contact with the rollers. To get a uniform current on the 12k tow it is necessary to spread the composite evenly, which is a complex process. Another problem that arises from uneven spreading is fibre damage, which depends on tension, so it is a compromise between resistance and fibre damage [70].

The process of continuous metal electro-deposition on a 12K carbon tow is quite complex, even though it is possible to coat fairly uniformly, ultra-thin deposition of Ni on 12K carbon fibre is possible. A major drawback of this process is that the coating of nickel on all fibres increases the weight of the carbon tow, which is a major drawback of electro-deposition of metal on carbon tow.

2.7 Summary

This chapter has discussed the need for metal coated spread carbon tow as a multifunctional material with several applications like EMI shielding, de-icing and the benefits of spread tow fabrics. This section also covered the major types of chopped fibre preforming processes, which are currently available in the market, along with the growth potential of those in the automotive industry. Finally, metal-coated fibres which are presently available were also discussed.

Critical Discussion and Justification for this Research

With the increased use of carbon fibre in the composites industry and the need for a greater degree of material utilisation has led to the research and development of multifunctional carbon fibre. In addition to mechanical performance applications, carbon tows are modified to add other functions like energy storage, stealth, real time structural health motoring.

Researchers have developed multifunctional metal-coated carbon fibres for EMI shielding using the electro-deposition process. This material can be used for reducing preforming costs in the automotive industry using the DCFP process with magnetic tooling.

The coating of every carbon fibre with metal, in electroplating has the disadvantage of a significant weight increase - thereby nullifying some advantages gained by using carbon fibre, and also adding to the complexity in processing of the material. This has led to the current research into novel approaches on coating carbon fibre with metal.

In this study metal-coated carbon fibre is developed using three techniques, the co-mingling of metallic micro-fibres, a coating with metallic powder and the printing of metallic gratings.

Chapter 3. Development of a metallisation process for carbon tow

3.1 Background

Carbon fibre composites have a unique place in the automotive, aerospace and wind energy sectors due their high strength to weight ratio and their thermal stability [2, 64, 66, 73, 74]. The composite manufacturers engaged in these areas are on the constant lookout to increase the efficiency of production of composite material, suitable for these sectors. Multifunctional carbon fibre development is the primary objective of this research; by coating it with metal and spreading it to reduce the bending stiffness properties.

3.2 Metallised carbon fibre

The advantage in using metallised carbon fibre (MCF) tow is that due to the magnetic attraction existing between ferromagnetic material and a magnetic field created either by a permanent magnet or by an electro-magnet, it is possible to make the chopped MCF conform to the mould surface without using positive extraction equipment. Composite automotive body parts that are made using metallised carbon tows can be handled by means of robots rather than manually during the manufacturing process enabling a big reduction in the manufacturing cost [75, 76]. The mould created this way, whilst enjoying the advantages of the DCFP process over the conventionally moulded automobile parts, will also be an improvement to the DCFP process, due to the absence of problems related to having a positive air flow process and the roboticised construction means that every item manufactured is the same.

In this study, a number of techniques for metallisation have been investigated a) co-mingling of metallic micro fibres b) coating with metallic powder and c) printing of metallic grating. The relative advantages and disadvantage of each technique are discussed.

3.3 Properties of MCF considered while designing the machine

The specific properties of the MCF tow that is manufactured by this process, depends on the subsequent applications for which they will be used. However generally the specific mechanical properties required from the metallised carbon tow can be given as follows.

a. **Stiffness**: sizing is used to reduce fibre breakages of the carbon tows. With size, the strength and the abrasion resistance of the carbon tow are increased, preventing chances of filamentation. The improvement in strength depends on the adhesion force between the fibre and epoxy size, size penetration as well as encapsulation of the fibres [77]. However the drawback in using the epoxy size is, it is capable of increasing the stiffness of the tow, thereby reducing the drapability or three dimensional conformance of the metallised carbon tow in the mould. To achieve optimum conditions the concentration of the sizing material was maintained between 0.8%-1.2%.

b. **Spreadability**: the thickness of the spread carbon fibres in the tow tends to affect its bending properties. The thicker the tow used, the higher the resulting bending tow rigidity. To bend the metallised tow significantly through the use of a magnetic field, the stiffness of the tow needs to be within acceptable levels since higher stiffness values will result in higher electricity usage when using an electromagnetic field. Therefore through experiment it was found the spreading the 12k carbon fibre tow that has fibres of 5-8 microns [8] to a width of 10-12 mm and to a thickness of 0.06 mm gives a stiffness that is of sufficient flexibility for the present work.

c. **Magnetic pull**: tow metallisation with a ferromagnetic material is the key requirement to create a magnetic pull in this study. Therefore depending on the thickness of the manufactured component, an optimum weight percentage of ferromagnetic material per unit area needs to be used. Furthermore if the carbon tows were less metallised, electromagnets that are used in mould handling will require more electricity.

3.4 Co-mingling of metallic micro-fibres

Cobalt wire can be merged within the carbon tow in order to achieve metallic properties of the resultant tow. Epoxy water-based size was used to help in creating a bond between both components. One of the limitations, restricting doubling between carbon tow and cobalt wire is the tow spread.

The process has been outlined in **Figure 3-1**, in this process carbon tow and cobalt wire were passed through a water-based epoxy bath to bond the cobalt wire with the carbon tow, at same time creating an inter-cohesion force with the carbon fibres themselves. This cobalt-carbon tow was then passed through an air nozzle to aid spreading and the washing off of excess resin, then the tow goes through the spreading rollers in order to flatten the resultant tow. The tow is then passed in front of an infra-red heater and finally wound on to bobbins after drying.

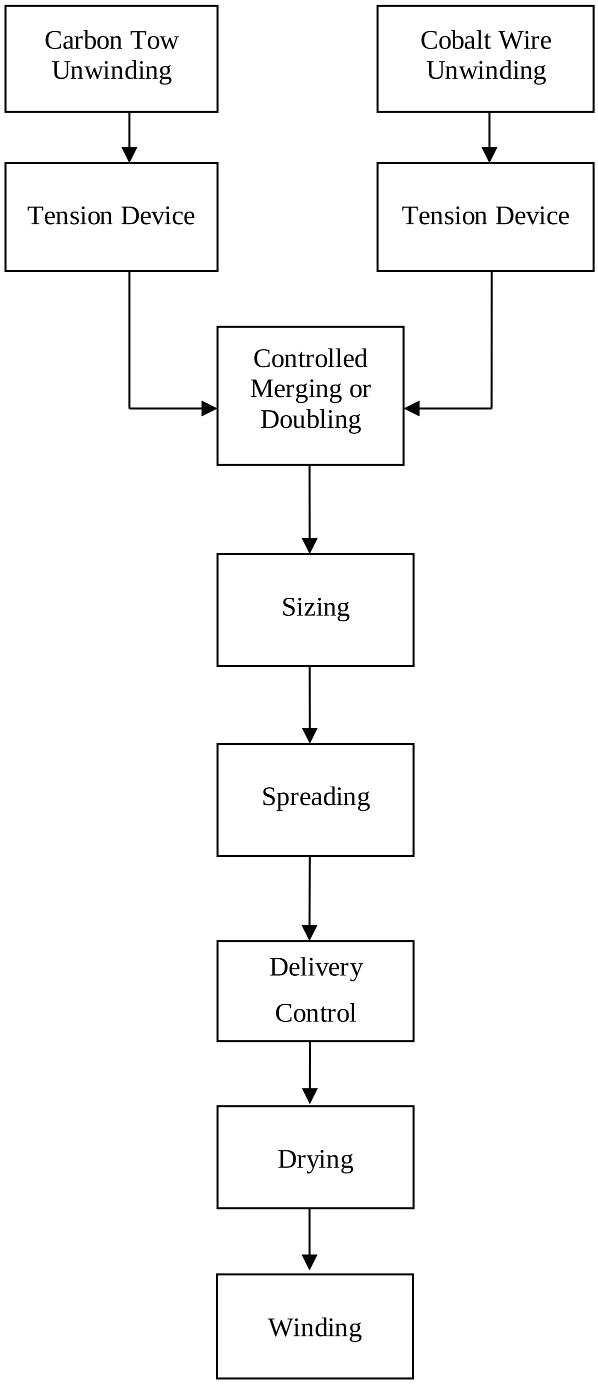

Figure 3-1 Process flow of the co-mingling of metallic micro fibres

It can be seen from **Figure 3-2** that the carbon tow was let off using a positive feeder and the cobalt wire was also let off under tension.

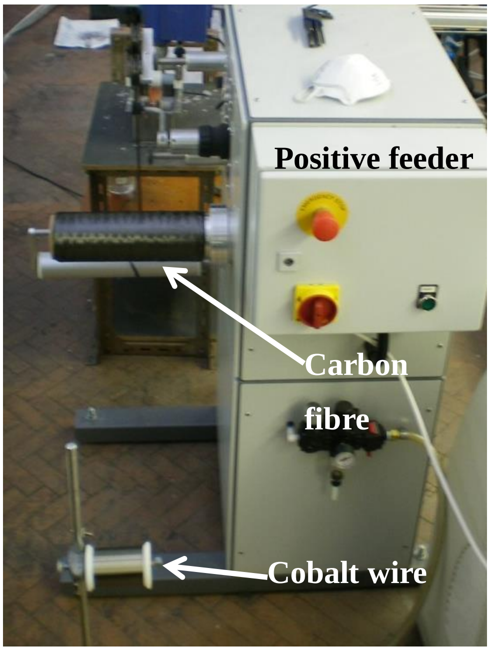

Figure 3-2 Carbon Tow and Cobalt wire letting off under tension

To bond the cobalt wire on to the carbon tow, the commingled tow was passed thorough a size bath containing water based epoxy resin as shown in **Figure 3-3**. The amount of size content determines the adhesion between the cobalt wire and the carbon tow. If the size is increased the bending stiffness of the tow also increases.

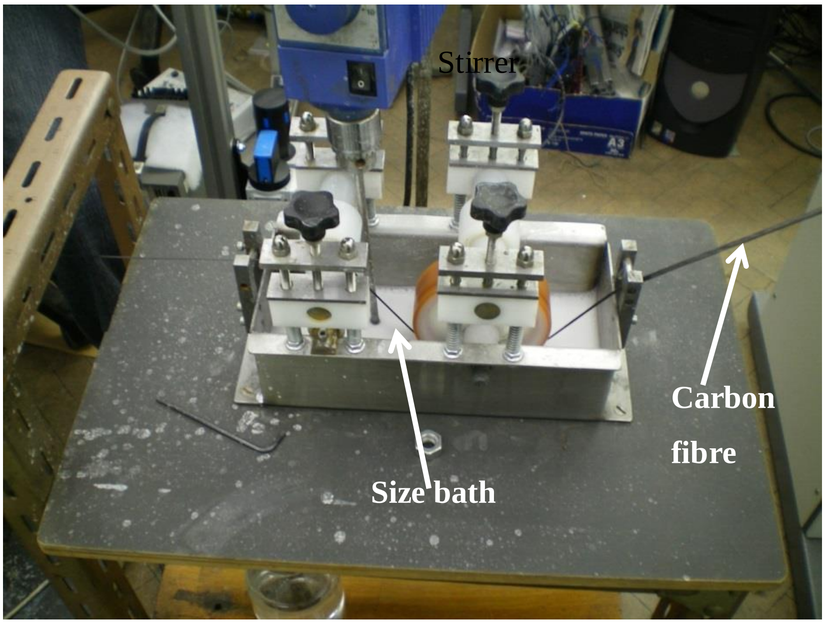

Figure 3-3 Size bath

Commingled tow was then spread to reduce the stiffness of the tow by passing through a series of rollers and an air nozzle illustrated in **Figure 3-4**. The spreading of the tow was found to be complicated, due to the commingling of fibres using filaments of different linear densities. Tension control in both the fibres was critical to the spreading of the tow.

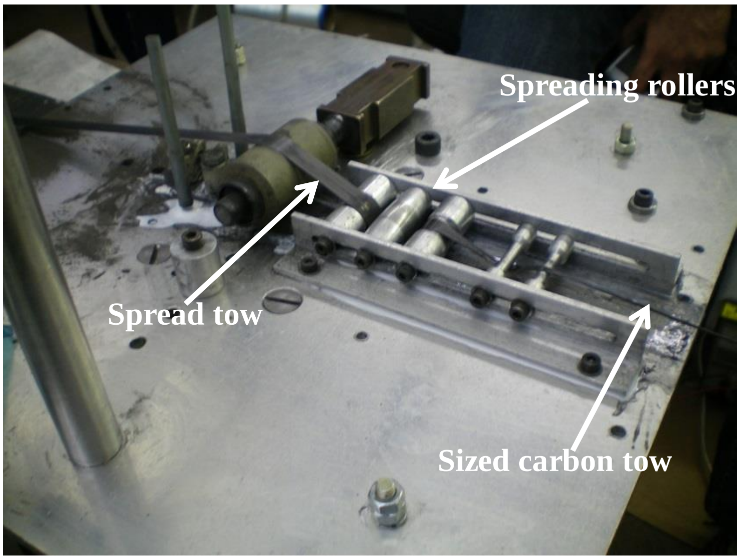

Figure 3-4 spreading rollers

The spread tow is then passed through a series of infrared heaters as can be seen in Figure 3-5.

The length of infrared heating zone determines the output speed of the process.

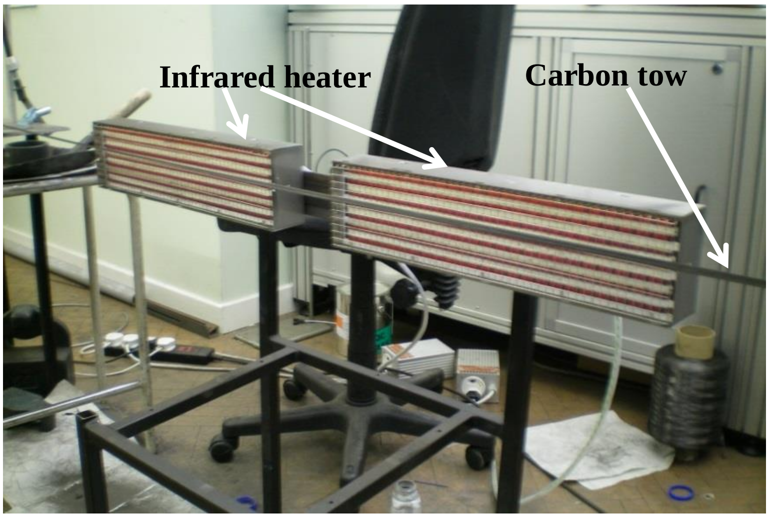

Figure 3-5 Infrared Heaters

The commingled tow is then finally wound on to a bobbin, using a cross winding system as depicted in **Figure 3-6**. In this system the bobbin stays in one position and winds, at the same time a reciprocating eyelet takes the commingled tow to and fro during the winding. It was observed that the moving eyelet was crushing the tow.

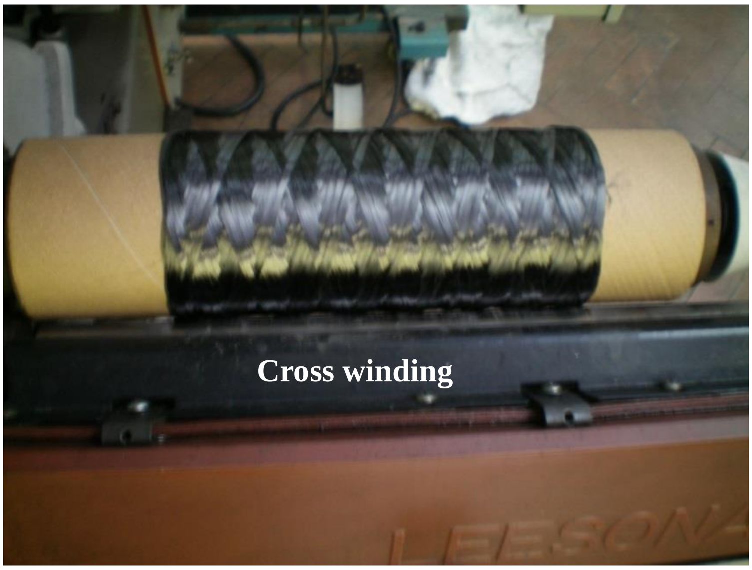

Figure 3-6 Winding

Cobalt wire and carbon fibre commingling has the advantage of having a homogeneous ratio of carbon fibre and cobalt wire throughout the length of the tow. The tow quality with respect to adhesion between the fibres depends primarily on the size content.

The embedding process was practical since there was no metal powder dust or flying fibres. The main disadvantage of this process is the high probability of moving cobalt wire to the edges of the carbon tow, resulting in de-bonding due to tension variation. Finally, it is difficult to maintain equal tension in the metal wire and the carbon tow during co-mingling.

3.5 Coating with metallic powder

The metallisation concept of this process is to deposit a continuous layer of nickel powder on to the surface of the carbon tow. A small quantity of size was added to bond the nickel powder on to the surface of the carbon tow.

This technique involved the coating of the nickel powder only on one side of the carbon tow. The carbon tow was passed through the water epoxy bath, spread using an air nozzle and rollers. The nickel powder was then dropped on to the carbon tow using a mesh that was vibrated using pneumatic actuators. The metallised tow was then dried using an infrared heater and finally wound on to the bobbin. The process flow of this is given in **Figure 3-7**.

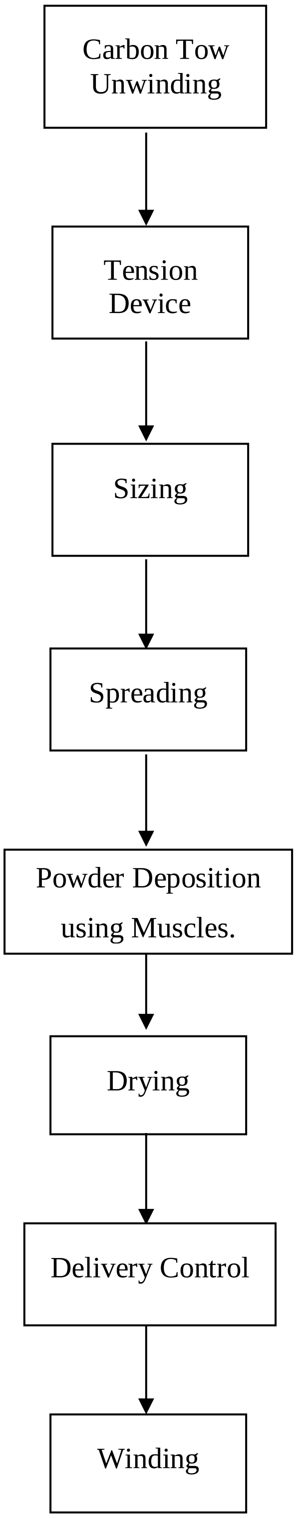

Figure 3-7 Process flow of the metal deposition process

As can be seen in **Figure 3-8** carbon tow was let off under tension using a positive feeder and is then passed through a size bath. The size bath was constantly stirred to maintain the consistency of the size bath.

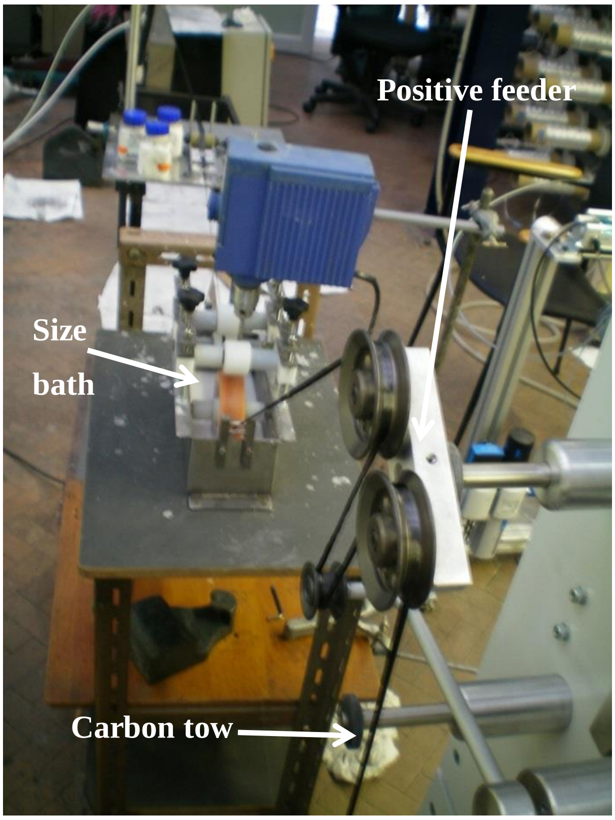

Figure 3-8 Carbon tow let-off under tension into the size bath

When the carbon tow passes through the size bath it has a tendency to become a tubular shape. If the tow is of a tubular shape its bending stiffness also increases. In order to reduce the bending stiffness the tow is spread by passing through a set of spreading rollers as pictured in **Figure 3-9**, at the same time an air knife was used to wash off the excess size, and also helped in spreading the sized tow.

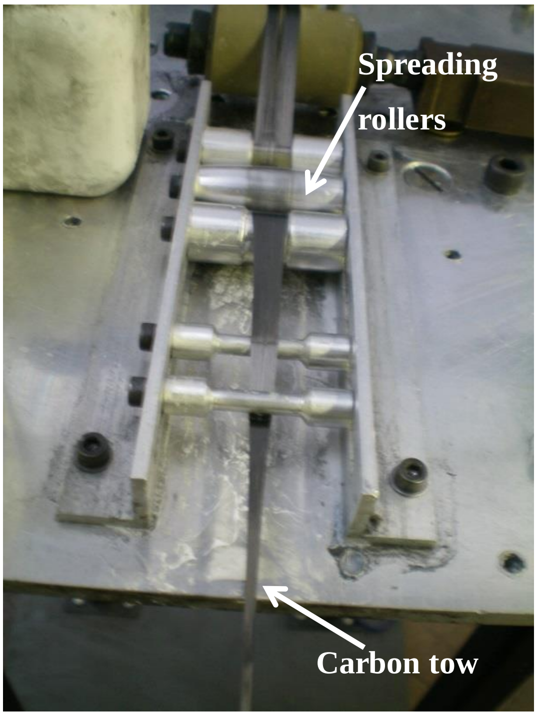

Figure 3-9 Spreading of the sized tow

The powder was dropped on to the sized and spread carbon tow using a mesh, which is connected to a pneumatic muscle that vibrates the mesh as shown in **Figure 3-10**. The vibration of the muscle can be controlled to increase or decrease the quantity of powder required to deposit on the surface of the tow. This process can also be incorporated inside a chamber system to control the excess powder dropping on the surface. Furthermore, altering the mesh size can control the quantity of the metal powder.

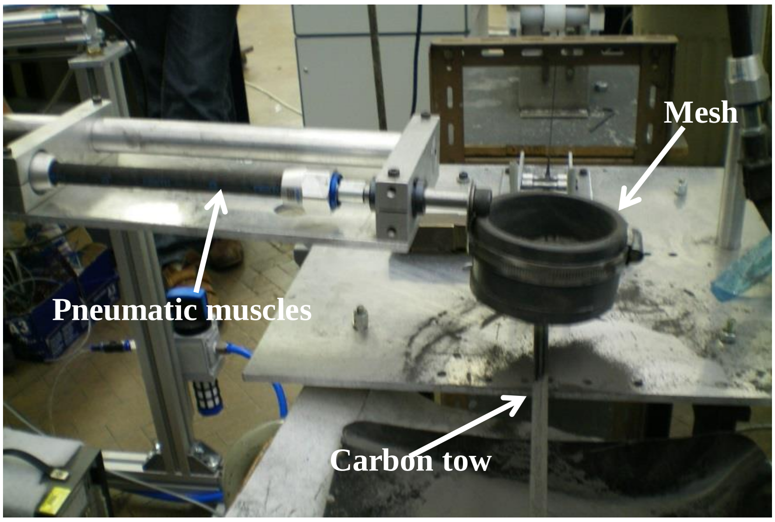

Figure 3-10 Nickel powder was dropped on to the tow using mesh vibrated using pneumatic muscles.

The sized, spread and nickel powder deposited carbon tow is passed in front of a series of infrared heaters for curing and this is pictured in **Figure 3-11**. The process speed mainly depends on the curing procedure. If the speed of the process needs to be increased then the length of the infrared heater had to be increased.

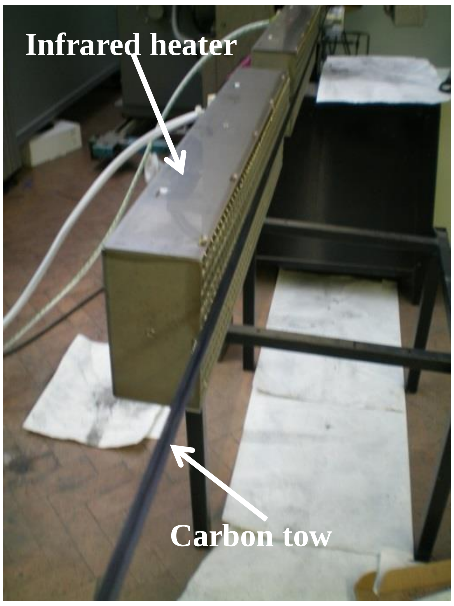

Figure 3-11 Drying of Nickel powder coated carbon tow

One major problem of nickel powder deposition was that nickel powder fell off the carbon tow when in contact with the guide rollers as shown in **Figure 3-12**. To reduce this problem the quantity of size can be increased but then a new problem arises, which is an increase of bending stiffness. Therefore it is a compromise between the powder loss and bending stiffness.

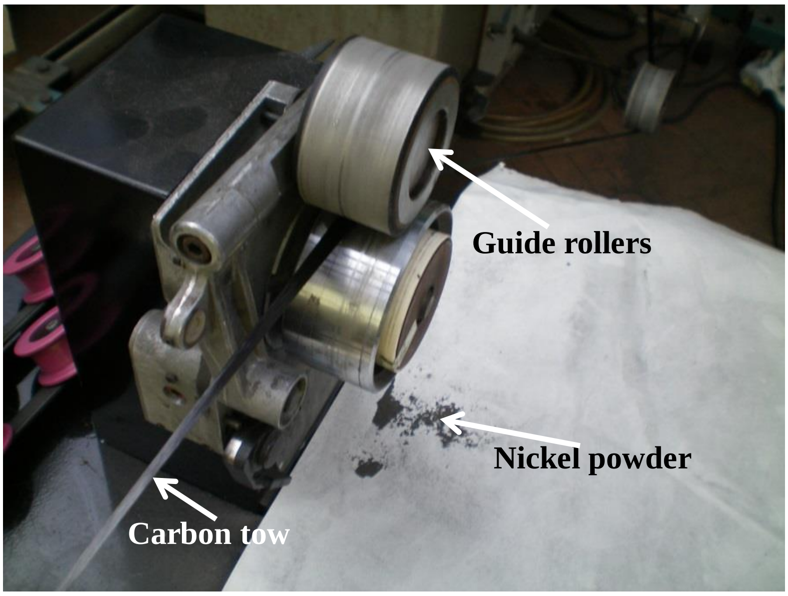

Figure 3-12 Guide rollers

The tow was then wound on to a bobbin using a cross winding system, in this process the bobbin stays in one position and winds as shown in **Figure 3-13**. At the same time an eyelet takes the tow back and forth in the transverse direction during winding. One problem of this winding set up is that the moving eyelet crushes the tow, thereby increasing the bending stiffness of the tow. It also causes powder to fly off during winding.

Figure 3-13 Cross winding

The deposition process allows the carbon tow to be metallised throughout its full width. The tension control was found to be easier compared to the previous cobalt wire embedding process. In addition, the homogeneity of the nickel powder metallised tow was found to be improved. The main problem of this process was the considerable loss of nickel powder from the surface of the carbon tow, especially throughout the drying zone. This loss also affected the efficiency and consistency of metallisation. The dropping or flying nickel powder also has environmental disadvantages.

3.6 Printing of a magnetic grating

As a third trial of developing a process to produce a metallised carbon tow, focus was concentrated on eliminating problems of previous techniques, such as losing nickel powder in the second technique and non-uniformity of magnetic properties while using the metallic wire due to the high probability of the cobalt wire coming off.

In this process, the nickel powder paste is prepared by mixing nickel powder with the diluted sizing material. This paste is then printed on to the surface of the carbon tow so that the nickel powder has no chance to fly off the tow surface and at the same time consistent metallic quantity is applied. Figure 3-14 shows the material flow throughout the printing machine.

The printing roller has been designed to give a constant print spacing and the full width of the tow was printed, that prevented the tow from contracting widthwise after drying.

The printing process was simple compared to the previous two processes and the disadvantages have been avoided. In this process the entire tow is not metalised, however the overall metallic properties are acceptable and the process is very flexible to achieve different levels of metallisation that can be controlled by both print spacing and the concentration of nickel powder within the paste. Overall performance of the printing process was industrially and commercially viable. Detailed explanation is given in section 3.7.

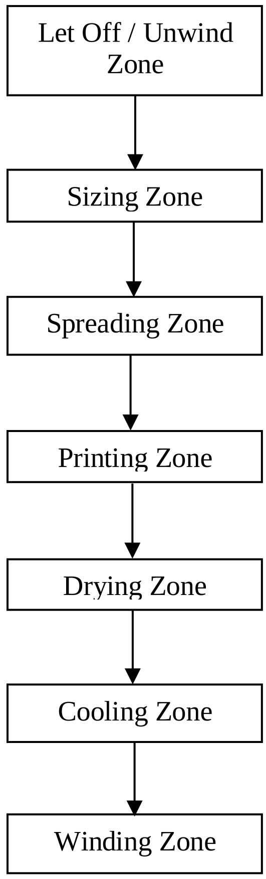

Figure 3-14 The process of epoxy nickel paste printing

3.7 Prototype Machine Development

In developing a manufacturing process to create MCF tows, the research carried out revealed three possible MCF manufacturing techniques. These techniques can be given as co-mingling of metallic micro fibres together with the carbon fibre tow, coating of metallic powder on carbon fibre tow and printing of a metallic line pattern on the carbon fibre tow. During the research work carried out to find the relative ease, suitability and the cost advantage of each of the process over the other two processes, printing a metallic line pattern was found to be performing better that the others. Therefore a production scale prototype carbon tow-printing machine was thus developed in order to produce metallised carbon tows as depicted in **Figure 3-15**. The machine was developed in such a way as to carry out the various steps of the MCF manufacturing in different zones of the machine. The development and functionality of these zones in this machine will be discussed in detail.

Figure 3-15 Prototype MCF printing machine

The prototype machine used to manufacture the MCF uses a water based epoxy resin as the sizing material, and a paste made of nickel powder mixed with the same epoxy as the printing compound. Experiments conducted have conformed that, printing the ferromagnetic paste provides one of the best methods of carbon tow metallisation, ensuring firm adhesion of the metal powder on to the tow. The prototype MCF manufacturing machine was built with seven sequential zones, namely; let-off, sizing, spreading, printing, drying, cooling and winding. **Figure 3-14** shows the material flow through various zones of the printing machine.

Throughout the process the tension and the speed of the tow were controlled precisely to ensure the MCF tow was correct in its cross-sectional dimensions and was completely cured. The function of the zones can be described as follows.

3.7.1 Let off zone

The let-off zone uses commercially available bobbins of carbon tow (Toray T700 60E) as the input material for the MCF manufacturing process. Here, the carbon tows from the bobbins are let- off under precisely controlled back tension through negative feeding. It was observed that maintaining the correct back tension at the let-off stage has a positive effect on the subsequent spreading that is carried out on the tow.

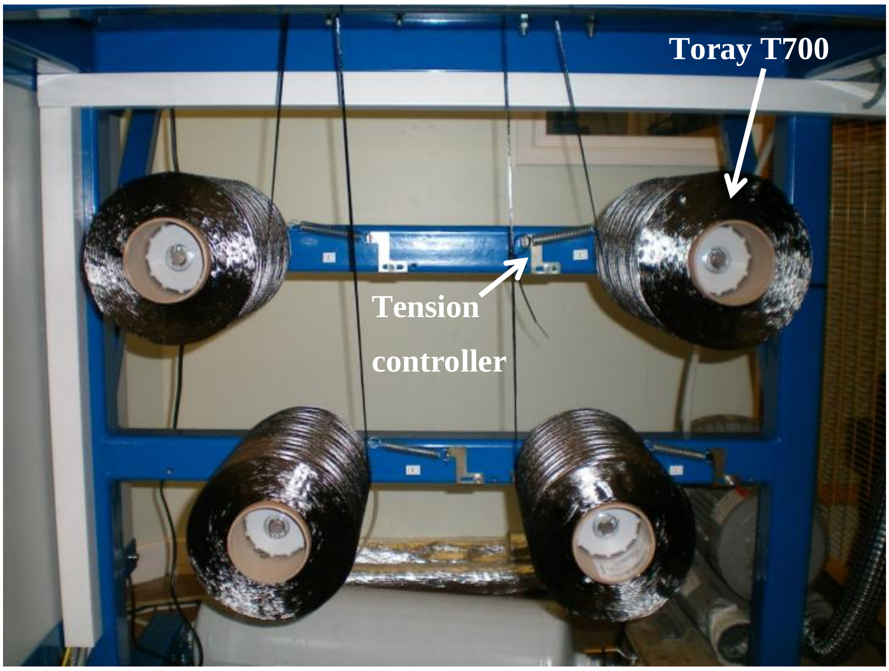

Figure 3-16 Carbon tow let-off zone of the prototype MCF printing machine

To ensure that tow receives no twist during the let-off stage, tow was removed in a direction perpendicular to the axis of rotation of the bobbin as illustrated in **Figure 3-16**. The current prototype machine was built to accommodate up to four bobbins of carbon tow.

3.7.2 Sizing zone

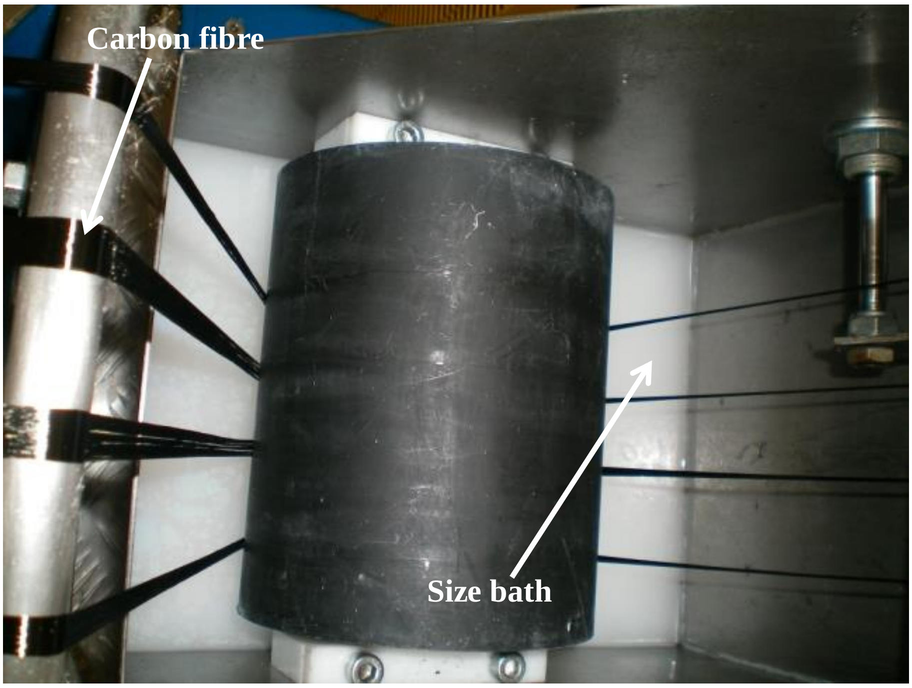

Figure 3-17 Sizing bath of the MCF tow production machine

It was found that if the tow is not soaked with a proper sizing solution, due to the adhesion of carbon fibres on the surfaces in its path, fibres get wrapped on rollers of the machine and prevent further processing of the tow material. Hence, in this stage, carbon tow from the let-off zone is run through a size bath to control the filamentation of the carbon fibres. Even though the tow that is introduced to the size bath seen in **Figure 3-17** is of rectangular cross section, on leaving the size bath, due to the surface tension forces resulting from the wetting of the fibres, the tow takes a tubular geometry. Therefore before the tubular carbon tow is introduced to the printing stage, it is next run through a spreading stage.

3.7.3 Spreading zone

Spreading of the tow is carried out to reshape the tow after its run through the sizing stage. Since the main reason for the tow to assume a tubular shape is the excess sizing in the tow, jets of air were used in the spreading stage to get rid of the excess epoxy size during the spreading of the tow and this can be seen in **Figure 3-18**.

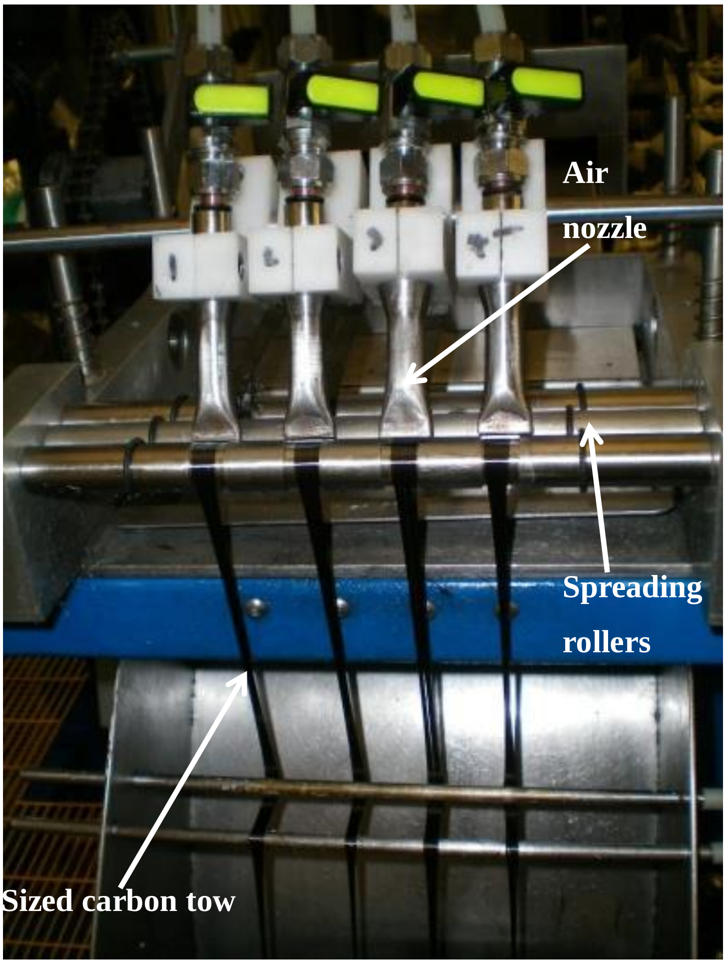

Figure 3-18 Spreading the sized carbon tow

Experiments showed that optimal tow spreading could be achieved using three sets of rollers. In the setup of the 3 rollers, the middle roller is designed to have a convex profile to carryout the tow spreading. The two outside rollers are positioned in such a way as to control the angle at which the tow is introduced to the middle roller and control the tension of the tow for optimum spreading. The tow that is spread this way to the correct width is thereafter introduced to the printing stage.

3.7.4 Printing zone

To maintain the shape of the optimally spread tow, the distance between the spreading and printing zones was made short. Since the MCF tow that is produced using this machine is ultimately to be used in a three dimensional mould, the optimal stiffness of the MCF tow is of highest importance. A screen printing system was designed to print epoxy nickel paste on to the surface of the sized and spread carbon tow.

Although the printing head can be designed to print any curvilinear shape on the tow, it is apparent that printing any shape other than transverse lines will greatly increase the stiffness of the tow. Therefore for printing the epoxy nickel paste onto the carbon tow, a cylinder comprising grooves (1mm deep, 1mm wide and spaced at 10mm) was used as shown in **Figure 3-19**. The dimensions of the groove were designed to deposit an optimum quantity of the epoxy nickel paste on to the carbon tow, in the best possible dimensions and frequency.

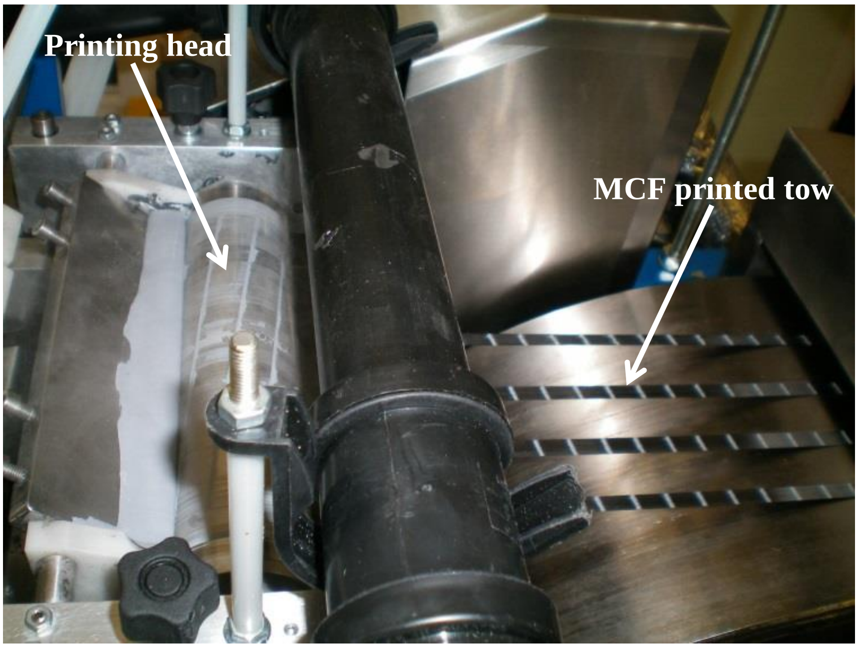

Figure 3-19 Printing of epoxy Nickel paste in the printing zone

3.7.5 Curing zone

Since the print paste is made with water to achieve the correct viscosity for printing, after printing the lines the excess water was removed through applying heat. During the production of the MCF tow, it was observed that, to obtain a rectangular cross-section MCF tow, contactless curing is unsuitable. To ensure the uniformity in the stiffness of the tow, the cross-sectional dimensions of the tow needs to be precisely controlled.

Figure 3-20 Curing the MCF on the heated drum

Therefore, to obtain the required tow dimensions after curing, it was found the curing has to be carried out while the required shape of the tow is maintained as seen in **Figure 3-20**. Therefore in the current process, curing was carried out by tensioning the MCF tow over a heated drum. To ensure the temperature of the drum surface is maintained uniformly, a thermic fluid that was kept at 110^0C, was cycled through the drum. To prevent the bubbling off of the excess water in the MCF tow during the curing, a hot blast of air was applied vertically on to the tow surface. The hot air additionally prevents heat loss from the surface of the cylinder and provides additional heat to cure the epoxy nickel paste.

3.7.6 Cooling zone

A cooling zone in the process was found to be essential since the epoxy in the MCF tow that comes out of the curing stage is still at a high temperature near 110^{0}C and is tacky.

Figure 3-21 Cooling of cured MCF tow

Winding at this temperature (without cooling) was found to result in all the tow layers sticking together on the bobbins preventing it from being unwound for subsequent use. Therefore the cured MCF tow was air cooled using a blast of ambient temperature air and this is shown in **Figure 3-21**.

3.7.7 Winding zone

Winding is the final stage in the prototype MCF production machine. During the design of the prototype machine, very few references were found on the winding of flat tow on to bobbins. In using conventional winding systems to wind the tow in the cross winding method, the tow was found to hit the walls of the eyelet and get crushed, leading to tow folding. Therefore a modified cross winding method was developed by oscillating the bobbin during winding, while holding stationary the U-shaped roller, which was used to replace the eyelet in the conventional system and this is shown in **Figure 3-22**.

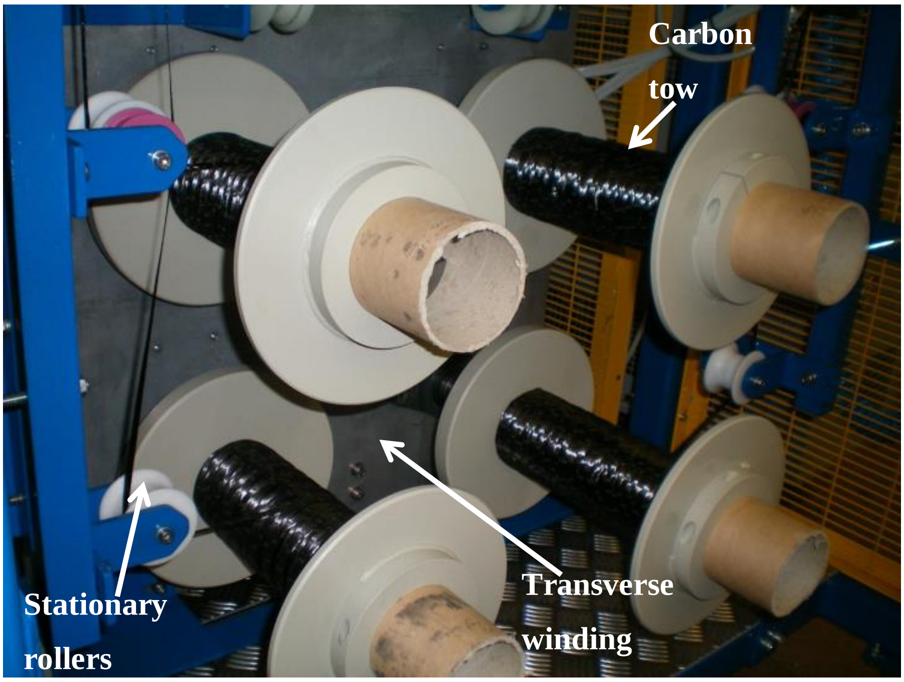

Figure 3-22 Flat tow winding of MCF tow

Since the harmonic motion of the oscillations tends to wind a larger amount of tow at the ends of the bobbin, the speed of the oscillations was controlled to achieve a uniform cross winding on the bobbin. As shown in **Figure 3-22**, end discs were used on the bobbins to prevent the collapsing of the winding at the edges.

3.8 Conclusion

The functionality of the carbon tow was increased by coating it with metal, so that the MCF tow can be used for non-structural applications such as an aid to preforming, icing, EMI shielding, and for mechanical properties when using spread tow for weaving or tow placement.

This research primarily deals with modifying carbon tow properties to have considerable magnetic characteristics. Composite automotive body parts that are made using metalised carbon tows can be handled by means of robots rather than manually during the manufacturing process. This will enable a big reduction of manufacturing cost. Three different techniques have been used to metallise the carbon tow, all the techniques have been evaluated, based on the consistency of the metallic characteristics of the resulting tows. The techniques used to metallise the carbon tow are:

- co-mingling of metallic micro-fibres;
- coating of metallic powder;
- printing of a magnetic grating.

Amongst the three methods, printing the metallic grating was found to be commercially viable. A production scale carbon tow-printing machine was thus developed in order to produce metallic carbon flat tapes. The development and functionality of the various zones of this machine have been discussed in detail; let off, sizing, spreading, printing, drying, cooling and winding.

Relevant tow properties such as stiffness, metallisation and spread have been discussed. Tow stiffness can be increased or decreased by changing the size concentration while metallisation can be controlled by changing the print spacing or by altering the nickel powder concentration in the printing paste.

Material development of the metallised carbon tow is discussed in chapter 4. Detailed characterisation of new MCF tow is mentioned in chapter 5. Process development and characterisation of the commingled carbon tow is discussed in chapter 6.

Chapter 4. Functionalisation of carbon fibre tows through metallisation for automotive composites

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4.1 Abstract

Directed Fibre Preforming (DFP) is a chopped fibre based composite manufacturing process used mainly in automotive and aerospace industries. Researchers have been developing both the material and the technology used in this process in order to produce carbon fibre based components more economically and efficiently than before. The current paper presents the manufacturing process of a metallised carbon fibre material for an advanced version of the DFP process that uses electromagnets for preforming instead of traditional suction airflow fibre deposition. The paper further presents mechanical and magneto-static modelling that is carried out to investigate the bending properties of the material produced and its suitability for creating 3D preforms.

Keywords: Tape, Magnetic properties, Finite element analysis, Preform

4.2 Introduction

Original equipment manufacturers of the automotive industry are facing strict government directives to reduce fuel consumption, thus reducing the emissions to meet the commitments of the Kyoto protocol [78-80]. A proven method of meeting the emission requirements is by reducing the weight of the automobiles [47, 81]. As published, reduction in weight of an automobile by 20% reduces the fuel efficiency by 8.4% [44]. To accomplish the weight reduction in automobiles, it is possible to reduce the weight of the moulded components used in automobiles by 50-70% by replacing metallic materials with composites [48, 53, 82]. However the manufacturing cost of composites based automobile moulded components remains one of the main concerns of automobile manufacturers since pure carbon fibre is 15 times more expensive than steel [67, 83]. To reduce the cost of the composites it requires low cost carbon fibres as well as high throughput production processes.

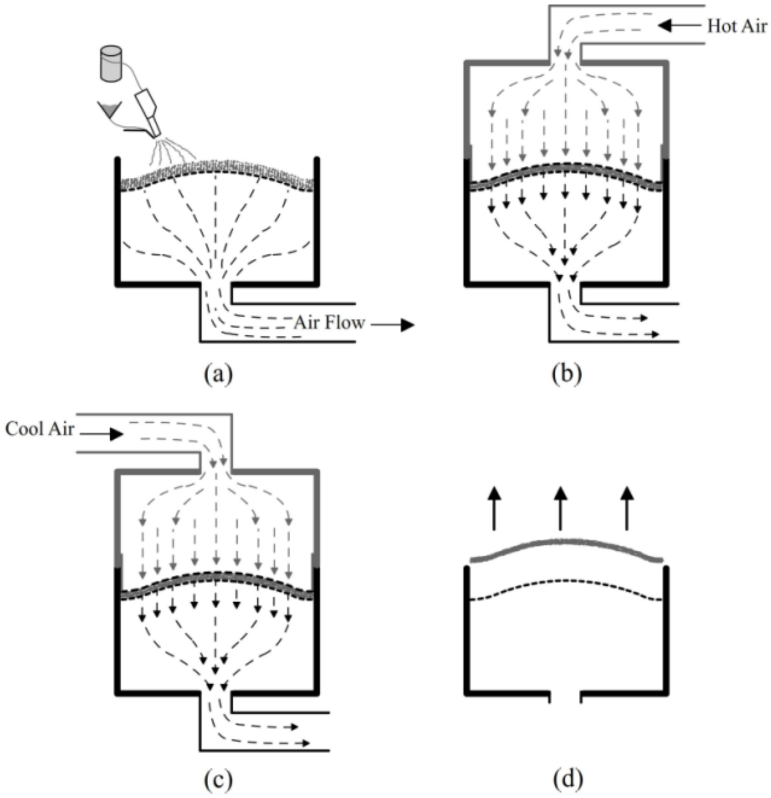

Figure 4-1 The conventional DFP process ; (a) Fibre deposition, chopped fibre and binder applied to lower screen, held by vacuum (b) Consolidation, upper screen compacts preform, hot air cures binder (c) Cooling, ambient air cools preform (d) demoulding, preform removed from the lower screen. [56]

As past research shows, chopped fibre preforming processes such as P4 (Powder Programmable Preforming Process) and DFP allow fibre deposition to be carried out approximately at a speed of 4 kg/min (Glass Fibre) , on to the mould surface [52, 56, 62-64, 66, 75, 84, 85]. The moulding process that uses chopped carbon fibres and the binder resin is called the Directed Carbon Fibre Preforming (DCFP) [55, 86]. This is an automated process through which chopped carbon fibres can be placed on to a 3D surface [55, 77] through air evacuation as seen in **Figure 4-1**. The process consists of chopping fibres and blowing them on to a mould surface to create the necessary moulded components. The binder which helps to solidify this shape is introduced during the placement of the fibres. However as reported by Harper et al [87], the low density carbon fibres tend to get disrupted, particularly on vertical surfaces of the mould tool, due to the suction air streams.

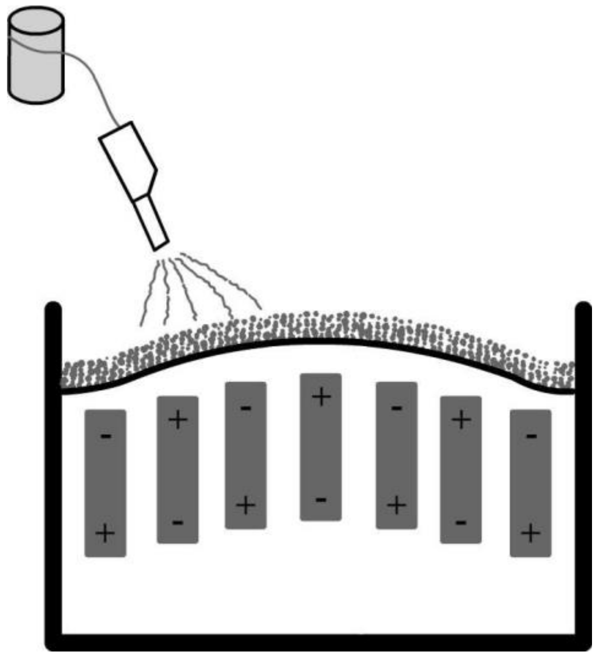

Figure 4-2 Chopped fibre applied to mould and held by electromagnetic force.

To overcome this drawback in the DCFP process, the composite research team at the University of Manchester has developed a metallised carbon fibre tow that can be placed on mould surfaces using a magnetic field. This material is aimed to be used in a mould that has an electromagnetic field as illustrated in **Figure 4-2** for tow placement instead of suction air, as in the case of the DCFP process, thereby avoiding the aforementioned carbon fibre disruption reported by Harper et al [87]. The concept of depositing metallised carbon tow on to a mould surface, in the presence of a magnetic field, with the help of DCFP has the same economies as that of the DCFP process due to the similarity in the tooling and accessories used in the preforming process [88]. In addition, the ability to handle finished composite components manufactured using Metallised Carbon Fibres (MCF) by electromagnetic pick and place robots, provides benefits in the subsequent assembly stages as well. All these advantages of using MCF, together with the reduced manufacturing times compared to other preforming processes like tow placement or weaving, makes MCF based Directed Carbon Fibre Preforming one of the main contenders in the composites manufacturing industries.

To visualise the magnetic energy for MCF tow placement, in an electromagnetic field similar to what it will encounter in the preforming process, it is important to investigate its magneto-static properties. Further, in order to observe the material's capacity to conform to the curvatures of the mould surfaces, it is important to carryout experimental and theoretical studies. These requirements are accomplished by the scientific experiments carried out and the associated finite element based analysis presented in this paper.

4.3 Process Development

In order to place carbon fibre tow using a magnetic field on to a mould surface, the tow needs partial metallisation. Here, an optimum metallisation needs to be carried out to ensure that the weight advantage carbon fibres have is not negated by the metallisation. To achieve these criteria, the MCF was designed with transverse lines of metallic powder placed at optimum predetermined distances with adequate quantities of ferromagnetic material.

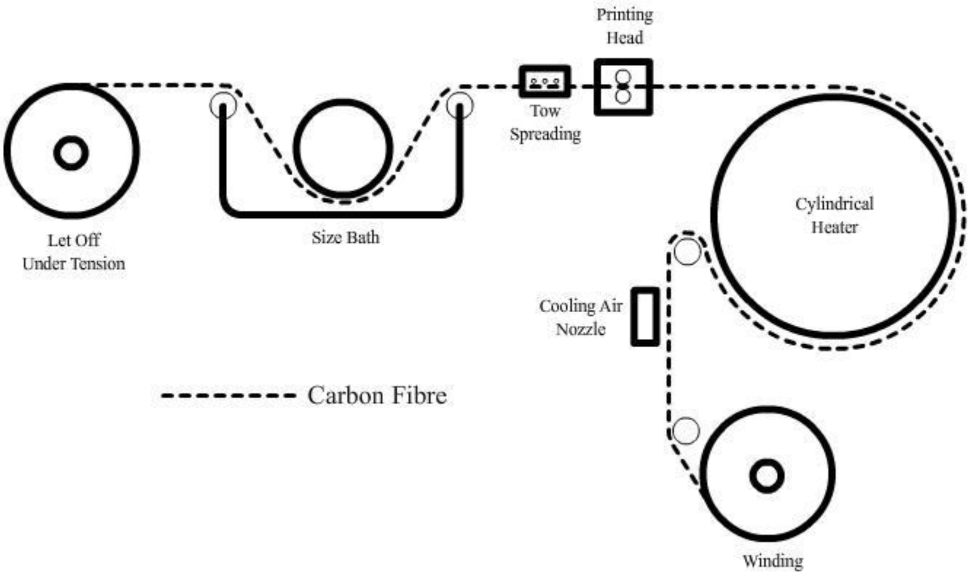

Figure 4-3 Schematic diagram of the process for printing of metallic grating

In developing a manufacturing process to create MCF tow with the above features, a prototype carbon tow-printing machine was developed. The process sequence of this machine is given in **Figure 4-3**. The specific properties of the MCF tow, this process is capable of producing, depends on the subsequent applications for which it will be used.

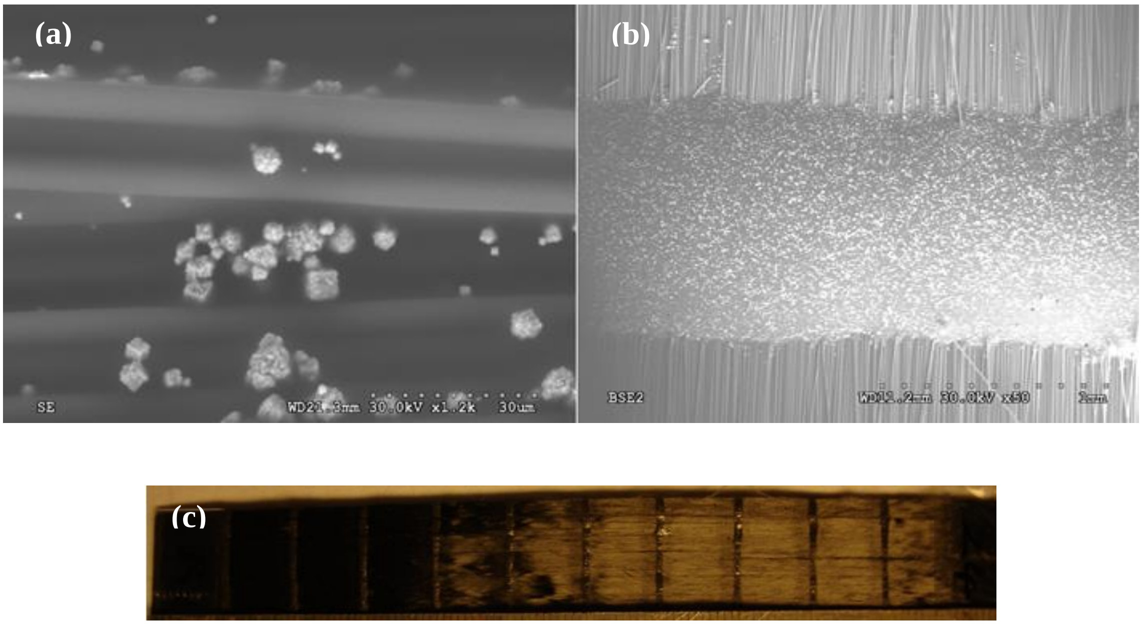

Figure 4-4 SEM image of the nickel powder used on the MCF (a), SEM image of the metallic print lines on the MCF (b) and digital image of the MCF flat tape (c).

The prototype machine built to manufacture the MCF tow uses water during the manufacturing process to prevent fibre damage. A paste made of nickel powder as seen in **Figure 4-4** mixed with Hexion EPI RZI water based epoxy was used as the metallic printing compound. Experiments conducted have confirmed that, printing the ferromagnetic paste provides one of the best methods of carbon tow metallisation, ensuring firm adhesion of the metal powder on to the tow as depicted in **Figure 4-5**.

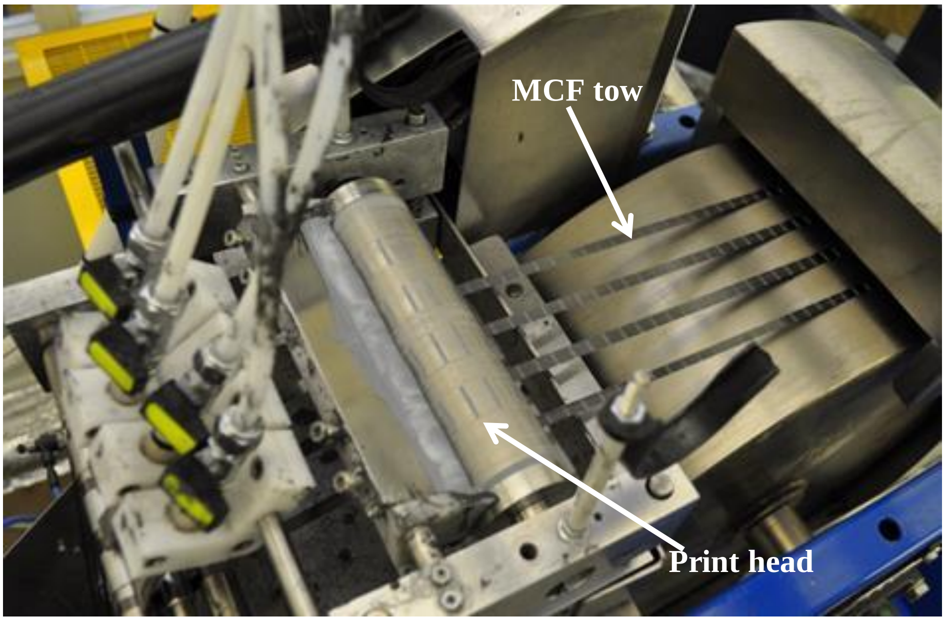

Figure 4-5 Printing of epoxy Nickel paste in the printing zone

The visual appearance of the MCF in a real product can be seen from the example below, where an automobile spare-wheel-well was constructed using the metallised carbon fibres as shown in **Figure 4-6**.

Figure 4-6 Spare wheel well made using metallised carbon tow (Bentley Motors Ltd.).

4.4 Experimental configuration

The micro scale of the carbon fibres practically prevents the carbon being handled in the form of fibres. Therefore they need to be in the form of a bundle of fibres or tows. Specifically in the present research, Toray T700 60E carbon fibre tows having a width of 6-7 mm and a linear density of 800 Tex, consisting of 12000 fibres was used. In processing these carbon tows to make them magnetisable, before the tows are chopped and placed on the mould surface, ferromagnetic material was incorporated in to the carbon fibre tows in the form of intermittent transverse lines. For the present work these lines were fixed at 1 mm x 10.435 mm repeating at 10mm intervals. The printing of these lines was carried out using a prototype MCF processing machine.

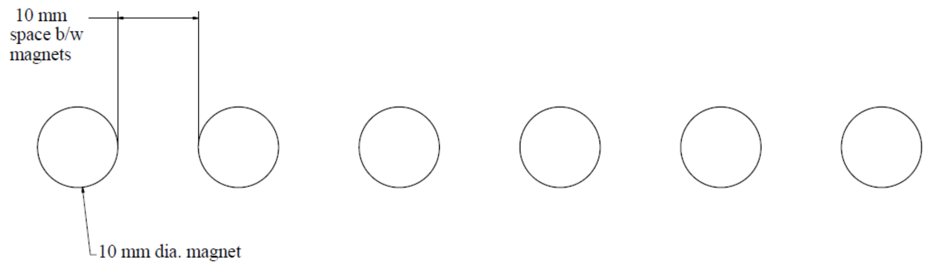

Figure 4-7 Arrangement of the permanent magnets to create the magnetic pull force

In practice an MCF tow is designed to be processed using a carbon fibre-specific chopper gun and may be chopped to a length of < 25mm since no fibre placement difficulties are experienced due to not using any air evacuation systems [55, 89]. By placing the mould in a magnetic field and by controlling the direction of the magnetic force, it is possible to force the carbon to bend and assume the curvature of the mould surface itself. This allows the resin infusion to be carried out for consolidating the component being moulded, without the problem of fibre escape.

Therefore in using the chopped MCF tow, the important parameters are; the magnetic attraction required to pull and hold the chopped tows on to mould surfaces, the effect of the orientation of the printed metallic lines in relation to the magnetic field on the attraction force and the strength of the magnetic field required to bend the chopped MCF on to the concave/convex mould surfaces. To observe the behaviour of the MCF tow under these conditions, the magnetic pull force tests were conducted in a magnetic field, created by a set of 6 permanent disc magnets as shown in **Figure 4-7**. The permanent magnets used were Neodymium-Iron-Boron disc magnets having a diameter of 10mm and a thickness of 10 mm.

In the test setup to observe magnetic pull force on the MCF tow as illustrated in **Figure 4-8**, where these magnets were used, they were held in the cross bar of a 2.5 kN Zwick/Roell tensile tester and the pull force was recorded using a load cell of 20N at a cross head speed of 5mm/min.

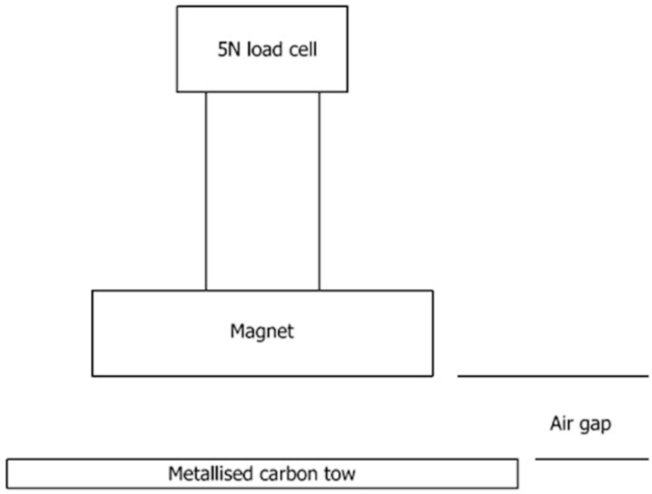

Figure 4-8 Tensile tester setup for measuring the magnetic pull force.

The test setup for observing the effect of relative position of the printed metallic lines to the permanent magnets was carried out by moving the tow sample in a lateral direction while the magnets were held stationary. To observe this magnetic pull force on a single printed line, the same test was conducted for a MCF tow having a single printed line.

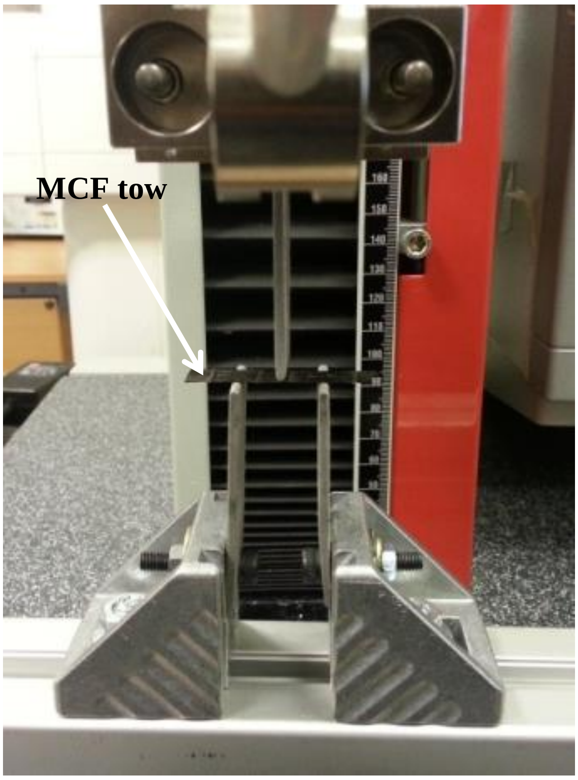

Figure 4-9 Three point bending test

In addition to these tests, to observe the bending properties of the MCF tow as a measure of its ability to assume the curvature of the mould cavity, a three point bending test was carried out according to the test standard BS ISO 5628:2012 shown in **Figure 4-9**. In order to measure the bending properties of the metallised tow under the influence of a magnetic field, a test was conducted as shown in **Figure 4-10** using a set of disc magnets.

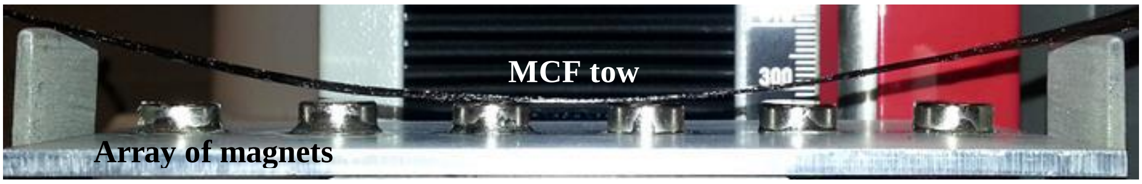

Figure 4-10 MCF tow bending under the influence of the permanent magnetic field

4.5 Mathematical modelling

In order to determine the scope of the MCF tow for engineering applications, it is important to know, through scientific analysis, its magneto-mechanical performance as a preforming material in composites. To fulfil this aim, it is imperative that a process of mathematical modelling and scientific validation of the performance of MCF is carried out. Since the MCF consists of magnetically inert carbon fibres holding the periodically printed metallic lines on one side of it, to determine the performance of the MCF in a magnetic field, an analysis of the effects of a magnetic field on the MCF tow need to be carried out. In this case, in the experimental environment, the magnetic field was created using an array of neodymium permanent disc magnets as illustrated in **Figure 4-7**.

The pull force exerted on a single metallic line of the carbon tow in the experimental set up due to a single neodymium permanent disc magnet can be described using the theoretical relationships below [90]:

$$F = A\frac{[B(x)]^2}{2\mu_0\mu_r} \quad \text{————————————————————} \quad \mathbf{(1)}$$

Where

F = magnetic pull force

A = area of the disc magnet

B = flux density on the MCF tow

μ_0 = magnetic permeability of free space

μ_r = relative magnetic permeability

The flux density of the disc magnet at a distance ‘x’ from the magnet can be given by [91];

$$B(x) = \frac{B_r}{2}\left[\frac{L+x}{\sqrt{R^2+(L+x)^2}} - \frac{x}{\sqrt{R^2+x^2}}\right] \text{---------(2)}$$

Where;

$B(x)$ = flux density at distance x from the magnet

B_r = remanence of the magnetic material

L = thickness of the magnet

R = radius of the disc magnet

Combining the equations (1) and (2)

$$F = A\frac{\left[\frac{B_r}{2}\left[\frac{L+x}{\sqrt{R^2+(L+x)^2}} - \frac{x}{\sqrt{R^2+x^2}}\right]\right]^2}{2\mu_0\mu_r} \text{-------(3)}$$

This shows that the relationship between the air gap height, from a magnet to the MCF tow, and the pull force, is defined by the equation 3. However in the present case, due to the multiple metallic lines and the array of permanent magnets in the setup, the magnetic pull force calculation is much more complex. Therefore the analysis in this case was carried out using the Ansys Workbench 14 suite of Finite Element Analysis software.

Since the carbon tow is magnetically inert, in the finite element analysis, only the effect of the magnetic field, on the metallic lines, was considered. For the finite element analysis, the material properties of nickel and neodymium permanent magnets were obtained from the ANSYS material properties. Due to the limitations on the computing power if the carbon fibres are modelled separately, the tow was defined as a homogenous tape having cross-sectional dimensions of 10.435 and 0.068 mm [92, 93]. The effective dimensions of the printed nickel powder lines were kept at 10.435 mm x 1 mm x 0.0004 mm.

4.5.1 Modelling approach

The static magnetic and the static structural analysis environment was set up and analysed in the Ansys Workbench environment. The magnets used for the setup were neodymium permanent magnets and the lines printed on the carbon tows were modelled with the properties of nickel. For the static magnetic analysis the element type used was Solid117 3D magnetic solid. For the static structural analysis the element types used were Solid187 tetrahedral elements, Contact174 elements for contact analysis, Targe170 for target faces, Surf154 for surface element modelling and Combin14 to represent the spring damper behaviour of the setup. Analysis settings also provides for large deflections in the setup.

To simplify the analysis carried out, initially a static magnetic finite element analysis was carried out to observe the effect of the horizontal separation of a single Nickel powder printed line in relation to the magnet at a constant gap of 1 mm as seen in **Figure 4-11**.

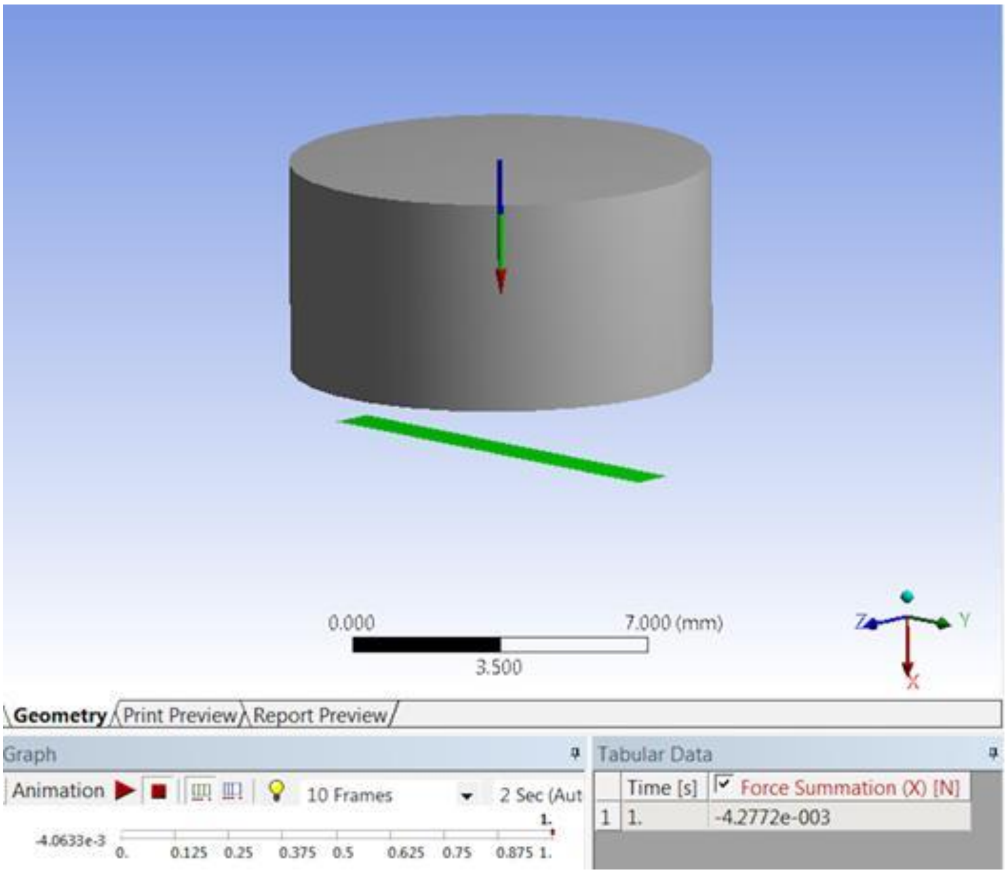

Figure 4-11 Magnetic force on a single magnet due to a single nickel print line

To observe the effect of an array of 6 magnets on a carbon tow printed with 7 lines of nickel powder mixed with epoxy, for the cases of relative horizontal and vertical position between the magnets and the printed lines as shown in **Figure 4-12**, another two finite element analyses were carried out.

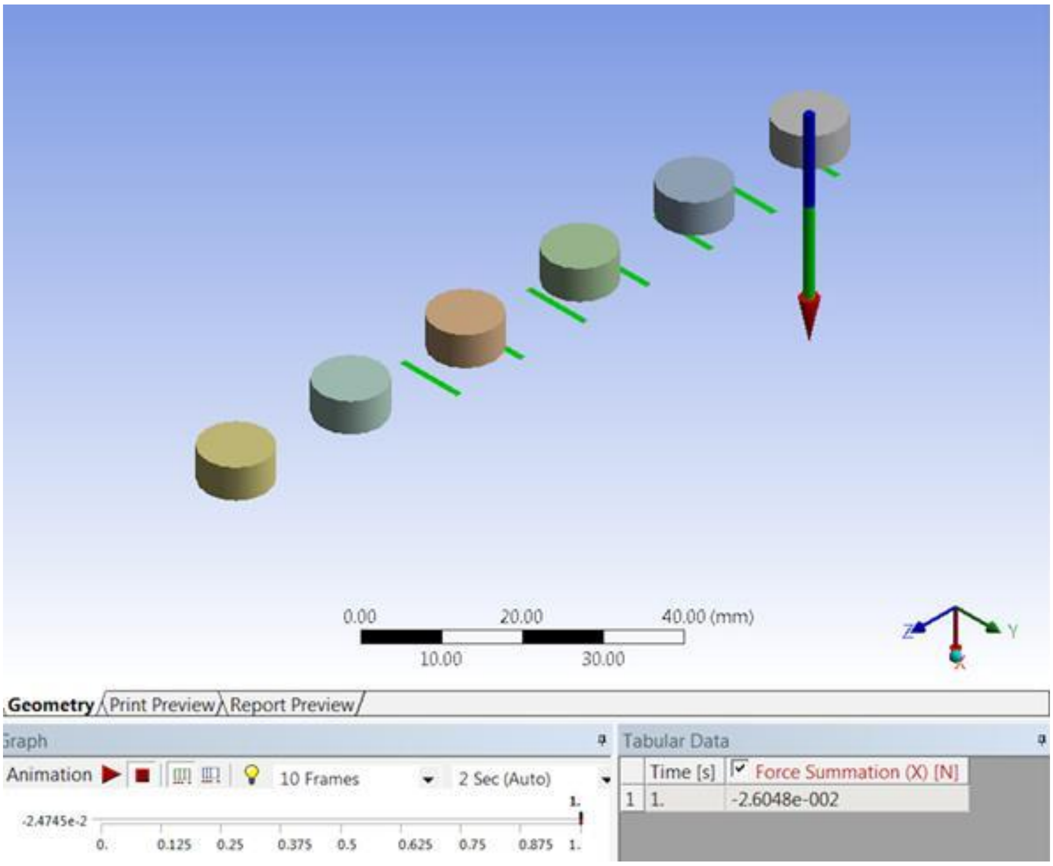

Figure 4-12 Analysis of the effects of horizontal and vertical position of the magnets on the printed tow

The bending rigidity of the MCF tow is an important parameter that will give an idea as to the carbon tow's resistance to bending and thereby indications of the energy requirements of tow bending. In order to model the bending behaviour and the bending curvature of the MCF tow, initially a three point bending test was carried out. Thereafter the bending rigidity values derived through this test was used in the static structural bending models, aimed at gauging the bending curvatures of the MCF tow.

To carry this out, the magnetic attraction forces on the printed nickel lines were determined from the static magnetic analysis. Observing that the MCF tow tends to go through a sudden impulsive bending movement, if the magnets are brought too close, the tow-magnet separation was maintained at a minimum safe separation distance of 10.55mm. The results of this tow bending model were later validated using the maximum bending depth observed in the experimental setup.

4.6 Results and Discussion

The static magnetic and static structural tests were conducted with the aim of gauging the performance of the metallised carbon fibre tow when it is used together with the magnetic tooling. The aim of the static magnetic tests was to see the effect of magnetic field strength on the MCF. By analysing the force experienced by the MCF depending on the separation between the MCF and the magnetic field and the relative orientation between the magnetic field and the MCF, it would be possible to find the fluctuations of the force experienced by the MCF due to their positions. To this end experiments were conducted with both single magnet – single MCF line and multiple magnet – multiple line carbon tows. The results of these tests together with the results of the mathematical validation using Ansys Finite Element Analysis are given below.

4.6.1 Single line single magnet test

The experimental setup has shown that handling the MCF tow and the magnets at a distance closer than 2mm is difficult. Therefore to conduct the experiments under an optimum magnetic force on the MCF tow, the separation was maintained at 2mm. The results were obtained with the horizontal displacement of the MCF tow from the centre of the tow by 1mm steps.

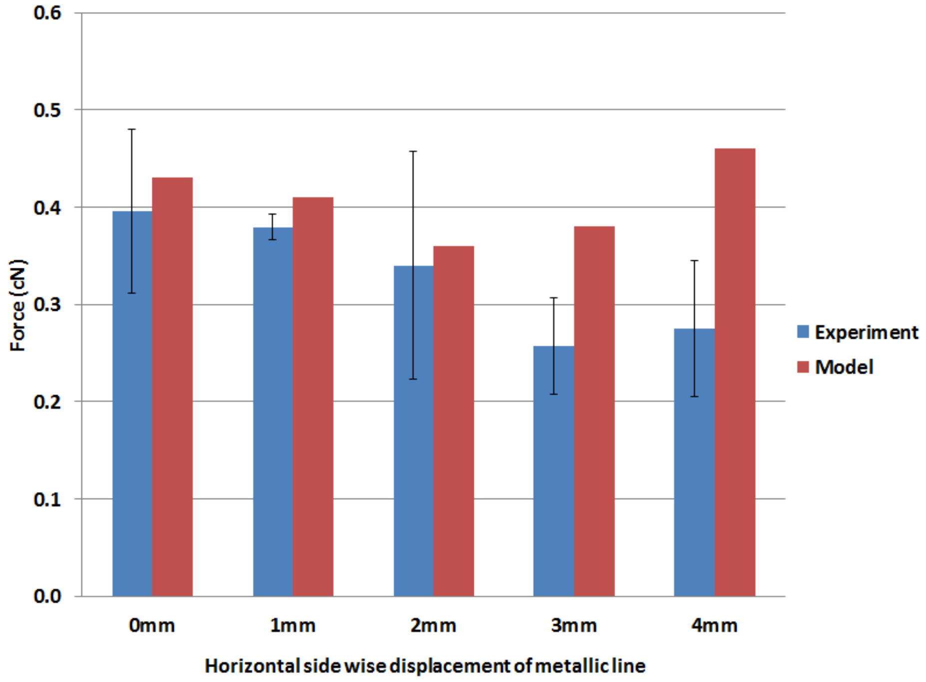

Figure 4-13 Comparing the force experienced by the metallic line at a sepearation of 2mm, both theoretical and experimental, for horzontal side wise displacements of 1mm from the centre.

As the results in **Figure 4-13** show, the change in the intensity of the force experienced by the MCF due to a transverse tow displacement of half its width is negligible. This behaviour was qualitatively validated by the Ansys mathematical modelling. The theoretical results are further explained by the graphical results presented in **Figure**

4-14. As observed the highest intensity of the magnetic force is experienced at the ends of the metallic lines rather than the middle.

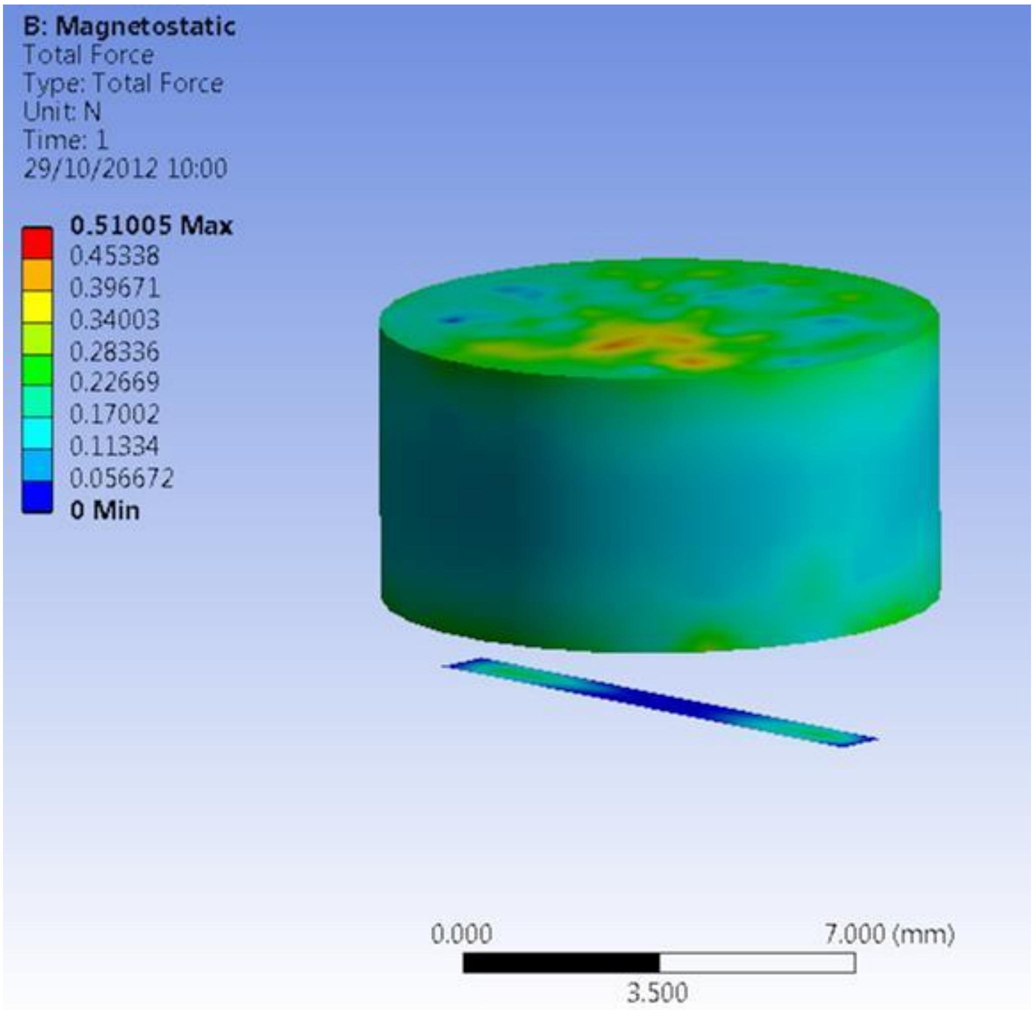

Figure 4-14 Total force experienced by the metallic line on the MCF tow due to a single magnet

4.6.2 Multi line multi magnet tests

Although the single metallic line single magnet tests were conducted to observe the effect on a single metallic line, to observe the force field experienced by a length of chopped tow, multi-line tow tests are essential. Therefore to provide these chopped tow lengths with a suitable magnetic field, an array of magnets was used.

4.6.3 Horizontal magnetic field shifting

The theoretical analysis carried out to observe the effect of longitudinal displacement between the magnetic field and the MCF in the horizontal plane has shown (**Figure 4-15**) that the change in force experienced by the MCF tow. This model verifies that it is possible to model a tool for the preforming process.

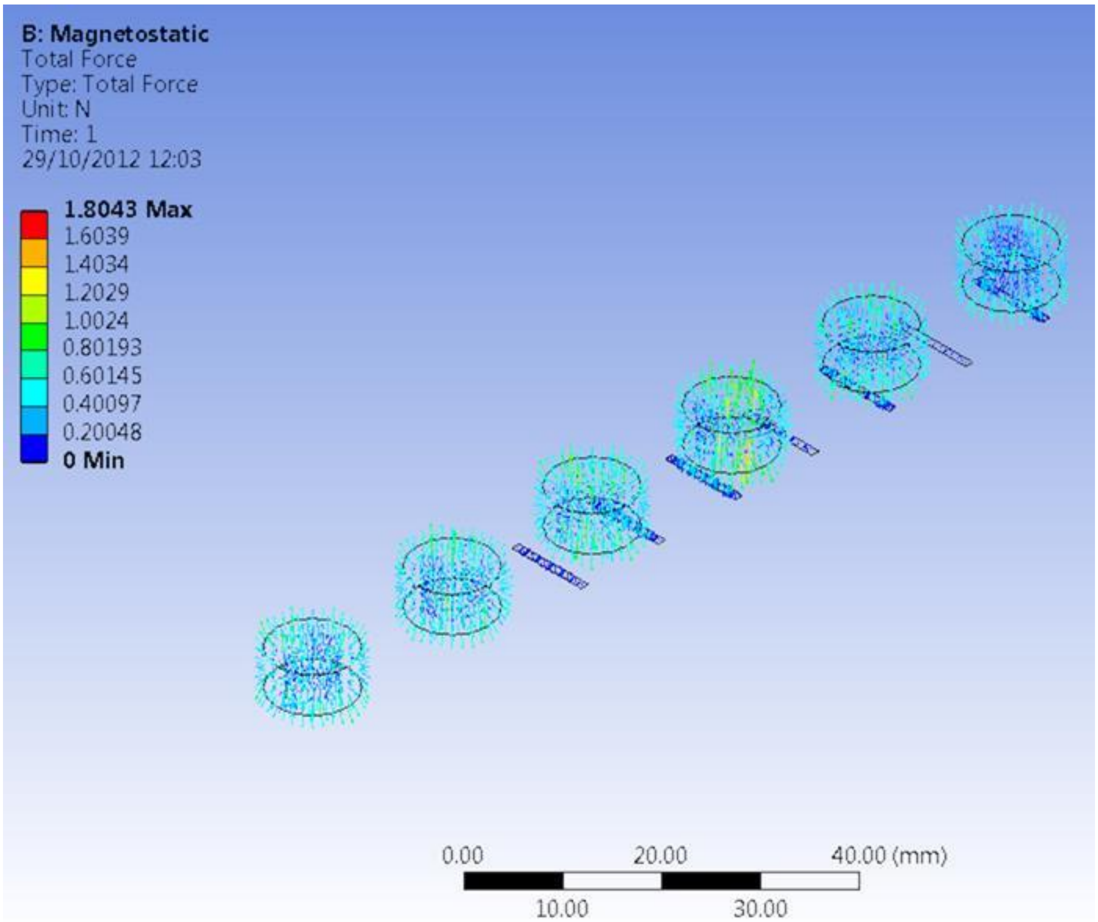

Figure 4-15 Total force experienced by the metallic lines on the MCF tow due to the magnetic field

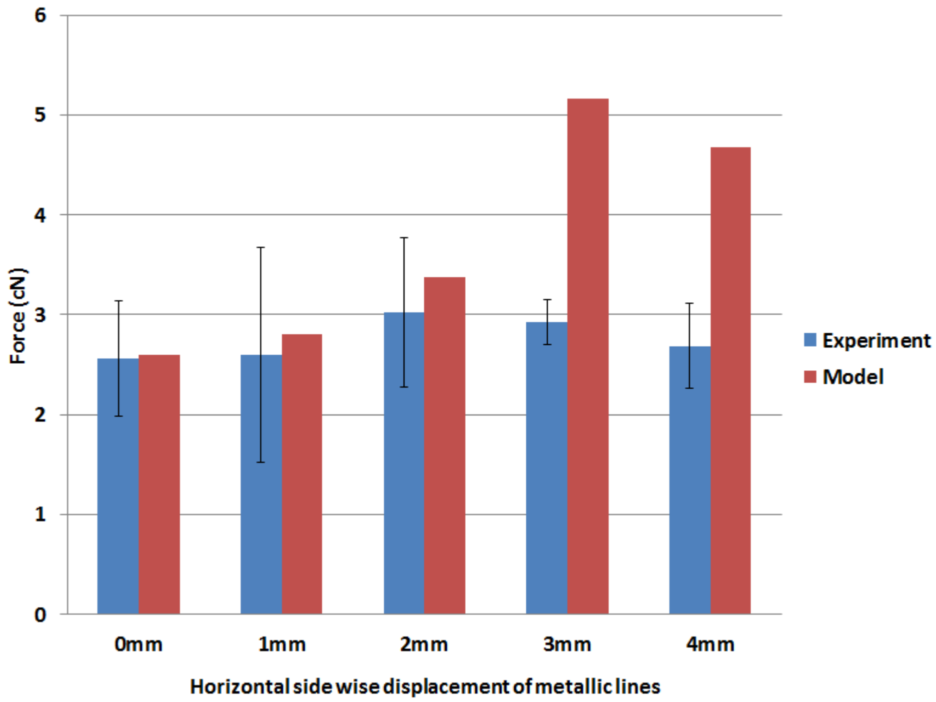

Figure 4-16 Comparing the force experienced by the metallic lines at a sepearation of 2mm, both theoretical and experimental, for horzontal longitudinal displacements of 1mm from the centre.

Therefore the current print line frequency of 1 line per 11 mm is sufficient to maintain a uniform force on all the printed metallic lines on the tow. The Ansys model created to represent this setup was validated by the experimental results shown in the bar chart given in **Figure 4-16**.

4.6.4 Vertical magnetic field shifting

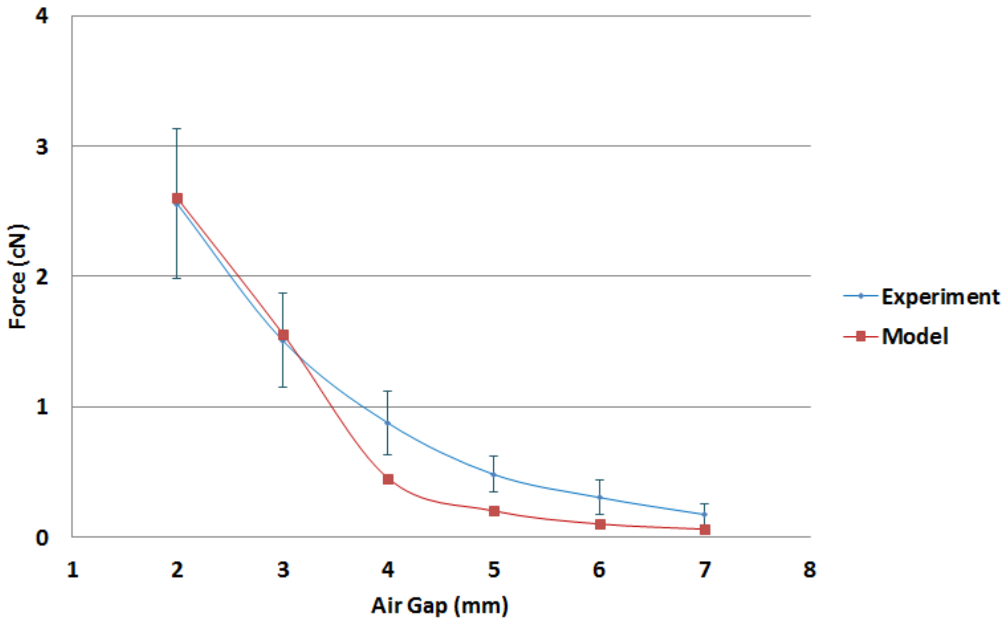

Figure 4-17 The theoretical calculation of the magnetic force experienced by the MCF tow depending on the distance between the tow and the magnet array and its validation using experimental results.

As observed in **Figure 4-17** the force experienced a increases at a very steep level near small sepearation distances while decays as the sepearation increases. Therefore this information is valuable to decide the number of layers of MCF tow to heat the magnetic field can hold at a time. Close validation can be observed between the Ansys model created to represent this setup and the experimental results.

4.6.5 Three point bending test

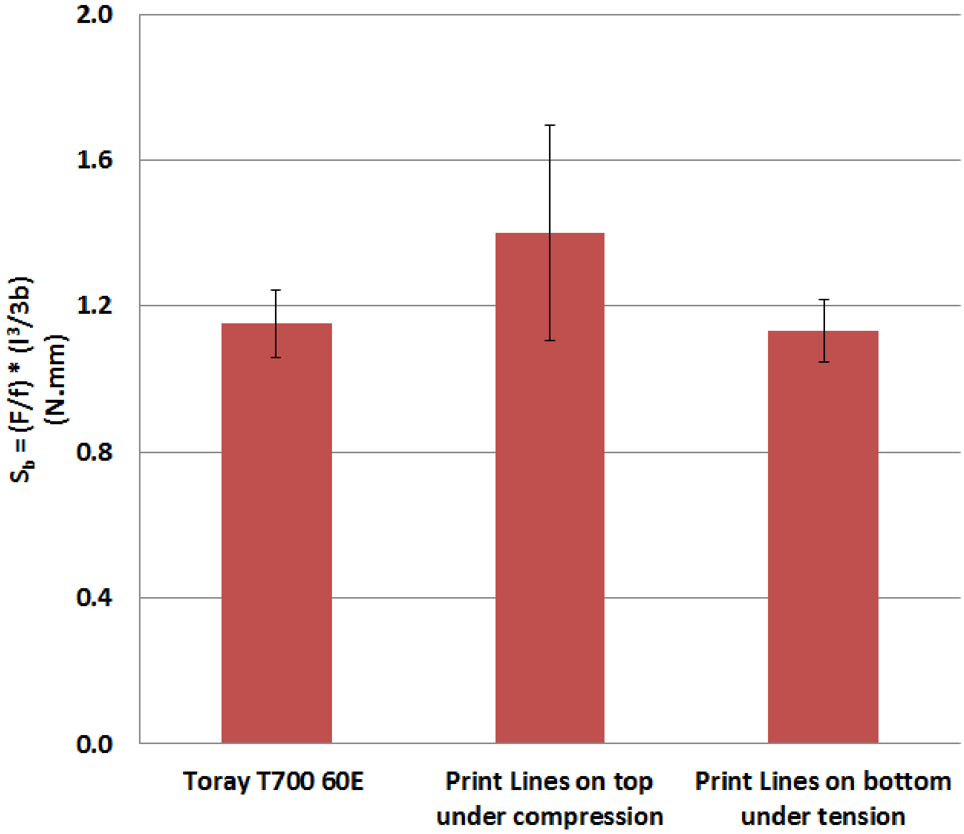

Figure 4-18 Bending rigidity calculation for MCF tow according to the BS ISO 5628:2012

F force, *f* linear deflection, *l* bending length, b specimen width

The determination of the Young's modulus for modelling the MCF bending was carried out according to the standard BS ISO 5628:2012. According to this standard the bending rigidity (S_b) is given by the following equation;

$$S_b = \left(\frac{F}{f}\right) \cdot \left(\frac{l^3}{3b}\right) \qquad \text{---------------} (4)$$

where

F = force,

f = linear deflection,

l = bending length,

b = specimen width

As **Figure 4-18** shows, the original bending rigidity of the carbon tow is largely increased due to the metallisation process. Also according to this figure, the bending direction, whether on the same side as the printed lines or in the opposite direction has no significant effect on the bending rigidity of the MCF tow. The Young's modulus value of 53 GPa derived from the experimental results given in **Figure 4-18** was used for the MCF tow material definition in the Ansys analysis.

4.6.6 Bending deflection under a magnetic field

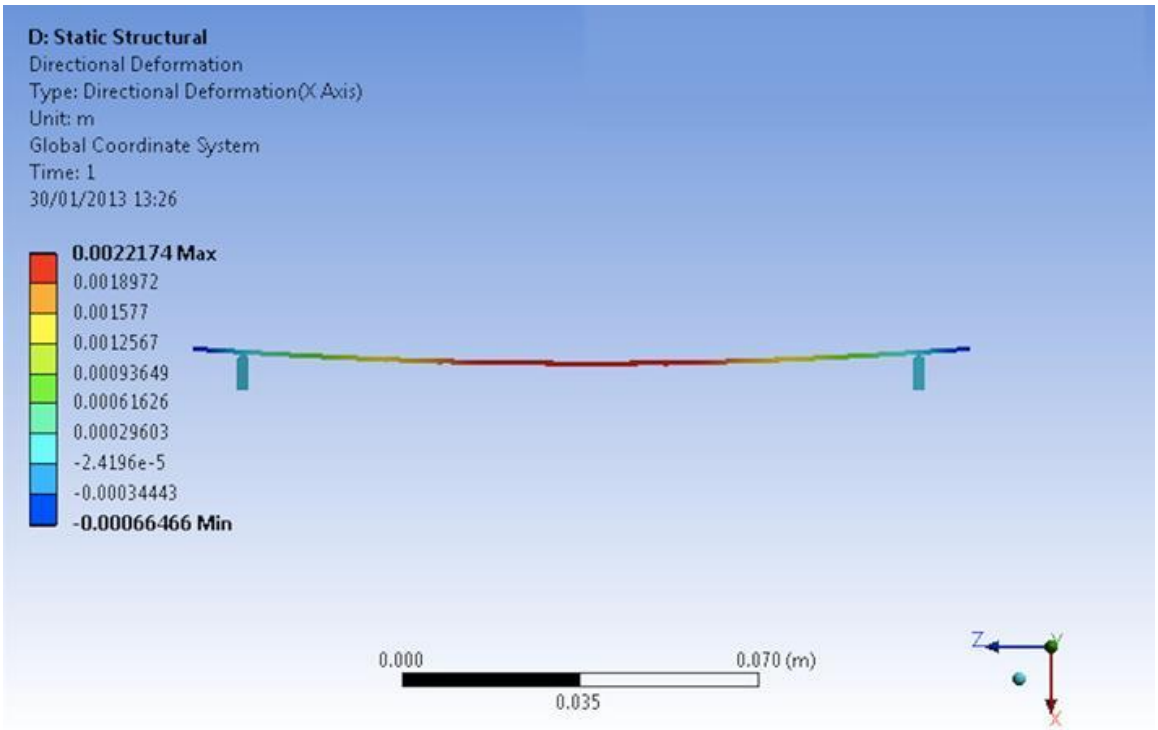

Figure 4-19 Results of the 3 point bending model for the MCF tow

The mathematical modelling of MCF tow bending was carried out to observe its capacity to assume the curvature of a mould surface. The validation of the model (maximum theoretical deflection of 2.22mm and the experimental value of 2.17mm) shows that the Ansys finite element model created for MCF tow bending seen in **Figure 4-19** is closely validated by the experimental results. Also observations show that beyond the maximum deflection of 2.17mm, the tow undergoes impulsive bending at very small bending radii due to the intense forces it experiences at close proximity to the magnet array.

4.7 Conclusions

Various iterations of machine designs that were studied have shown that the current design of the prototype MCF production machine is an excellent method for creating MCF tows. Tests have shown that due to the narrow width of the tow and since the tow is designed to bend in the transverse direction in the mould, a pattern of transverse lines is the best way to create the MCF tow. The MCF manufacturing process has been designed in such a way as to define the alignment of the printed metallic lines with respect to the carbon fibre direction accurately. This way while achieving the optimum flexibility in the carbon tow, the required static magnetic performance too is met. Although the introduction of metallic lines necessitates the use of epoxy resins which unavoidably increases the rigidity of the tow, in this particular situation, tests have shown that the rigidity hasn't increased to too high a level. Also it is recognised that much further work is needed to build on the success of this innovation to transfer this technology to manufacturing. Therefore while maintaining the advantages already established by the DCFP process, the MCF takes the DCFP to an enhanced level of functionality and efficiency by allowing the use of magnetic tooling.

The static magnetic and static mechanical tests carried out on the output of the MCF manufacturing process developed at the University of Manchester confirms the level of magnetic attraction, the ability of the magnetic field to handle the MCF tow, place it in a mould cavity and the ability to bend it to a required radius as well. Further the non-elastic sudden impulsive bending the tow undergoes was seen to be reversible within limits. The observation of uniform force distribution experienced by the tow for small levels of displacement and orientation changes with respect to the magnetic field confirms that a uniform performance can be expected for the frequency and the dimensions of the metallic lines in the tow. However the determination of optimum line density in a tow and the optimum line dimensions and at the same time the optimum epoxy metal combination to be used in the case of MCF manufacturing would necessitate further experimentation.

The studies have shown that, to achieve optimum levels of the general quality parameters expected from the MCF tow, it is possible to systematically engineer the tow, so that for a particular magnetic field strength, it is possible to determine the optimum mould wall thickness, the print line width, print line frequency and the quantity of powder in the lines. This information allows the optimum design of the print rollers, so that the general quality parameters are realised. To this end the authors plan to publish further work in future research publications on the characterisation of the MCF tow both magnetically and mechanically.

Acknowledgements

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References

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Chapter 5. Effect of size and ferromagnetic material on metallised carbon fibre tow used in the directed carbon fibre preform composites

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5.1 Abstract

This paper (continuation of paper-1) focuses on the mechanical properties of metallised carbon tow, which is the key enabling material for Directed Carbon Fibre Preforming (DCFP) process. The tows were manufactured with varying degrees of epoxy size and metallic powder. They were subsequently tested for bending properties to determine the effects of size concentrations on the stiffness of the tow. Further, tests were conducted to determine the relative magnetic effect due to concentration of the metallic powder. The experiments concluded the optimum level in which the size should be used, to achieve acceptable levels of bending stiffness. Further, the magnetic tests conducted showed the optimum shape for the introduction of the powder as well.

Keywords: Carbon Fibre, Metallised, Magnetic, Preforming, DCFP

5.2 Introduction

To create metallised carbon fibre tows, the authors has designed a manufacturing process capable of producing sized and metallised tows. It was observed that the process had the main independent variables; variation of the size concentration and the concentration of ferromagnetic powder in the carbon tow. As the dependent variables of the tow, the tow stiffness and its resultant linear density are considered. The stiffness of the resulting tow decides the electromagnetic field strength and the electrical power required to bend it to assume the shape of the mould. The low linear density of the MCF will contribute to preserving the weight advantage originally possessed by the composite components. These two properties together are of the highest importance to the manufacturing of MCF composites. The stiffness is mainly affected by the final quantity of the size the tow will carry. This quantity can be modified using different concentrations of the water based epoxy in the sizing bath. Determination of the optimum sizing level to achieve an acceptable range of stiffnesses in the tow requires extensive experimentation.

The weight increase of the metallised carbon tow used in the DCFP process is due to the ferromagnetic material. It is possible to carry out a simple calculation to find out the maximum weight of the metallised carbon tow for an electromagnetic field used for the moulding process. From this it is possible to calculate the maximum allowable mass of the metallic powder for the MCF tow. This quantity of metal powder can either be introduced uniformly or in a specific localised pattern. It has been reported that uniform coating of carbon fibres with metallic powder will increase the weight of the tow by more than 80%, which will result in the increase of stiffness of the MCF tow [94]. To reduce the increase in stiffness, it is possible to magnetise the tow by providing intermittent concentrations of metallic powder along the length of the tow. By controlling the geometry of the metallic powder deposit, it would be possible to have low stiffness and low linear density of the tow at the same time. It can be observed that while having transverse lines on the tow will contribute minimally to the bending stiffness of the tow, having lengthwise metallic powder lines will cause higher bending stiffnesses or fracture of the metallic powder deposits during use. In the case of incorporating metallic powder through geometrical line patterns, it is practical to have them transversely at an optimum line width and spacing. Therefore experiments need to be carried out to determine the optimum line width and spacing of the metallic lines on the carbon tow for a specific electromagnetic field used in the DCFP process. The pattern of metallic lines thus integrated can be termed a printed magnetic grating.

In integrating the metallic powder on to the carbon tow, unless it is applied together with an epoxy binder, the powder will not be held fast to the tow. This is because the sizing applied to the tow is not capable of holding a sufficient quantity of powder. Therefore in creating the epoxy-powder mixture for the printing of the metallic lines, experiments need to be conducted to find the optimum relative proportions of the epoxy and the ferromagnetic powder used.

The experiments were designed to use neodymium permanent disc magnets to create the magnetic field to apply a pull force on the MCF tow. The theoretical equations that describe the pull force can be given as [90]:

$$F = A\frac{[B(x)]^2}{2\mu_0\mu_r} \text{ ———————————————————— } \mathbf{(1)}$$

where

F = magnetic pull force

A = area of the disc magnet

B = flux density on the MCF tow

μ_0 = magnetic permeability of free space

μ_r = relative magnetic permeability

The flux density of the disc magnet at a distance ‘x’ from the magnet can be given by [91];

$$B(x) = \frac{B_r}{2}\left[\frac{L+x}{\sqrt{R^2+(L+x)^2}} - \frac{x}{\sqrt{R^2+x^2}}\right] \text{ ———————— } (2)$$

Where;

$B(x)$ = flux density at distance x from the magnet

B_r = remanence of the magnetic material

L = thickness of the magnet

R = radius of the disc magnet

Combining equations (1) and (2)

$$F = A\frac{\left[\frac{B_r}{2}\left[\frac{L+x}{\sqrt{R^2+(L+x)^2}} - \frac{x}{\sqrt{R^2+x^2}}\right]\right]^2}{2\mu_0\mu_r} \text{ ——————— } (3)$$

This shows that the relationship between the air gap height, from the magnet to the MCF tow, and the pull force, is defined by equation 3.

The typical pull force vs. airgap distance is graphed in **Figure 5-1** below.

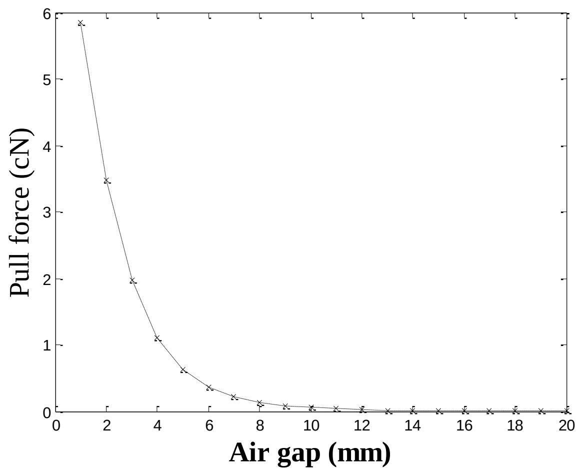

Figure 5-1 Theoretical relationship between pull force and air gap distance

5.3 Experimental Methodology

The manufacturing of the MCF tow is centred on the introduction of metal powder to the carbon tow. As mentioned earlier, this process is carried out through either applying the metal powder uniformly throughout the tow or by introducing the metal powder in a specific transverse line grating on the surface of the carbon tow.

The experiments were conducted using 12k carbon fibre tow having 7 micron carbon fibres. In the first method, to allow the metallic powder to adhere to the carbon tow, at the beginning, the tow was sized using a water based epoxy (EPI-REZ^{TM} from Hexion). Initially the metallic powder, specifically nickel powder Type 123, with typical grain size 3-7 microns, was applied uniformly on the spread tow using a sieve which was laterally vibrated as shown in **Figure 5-2**.

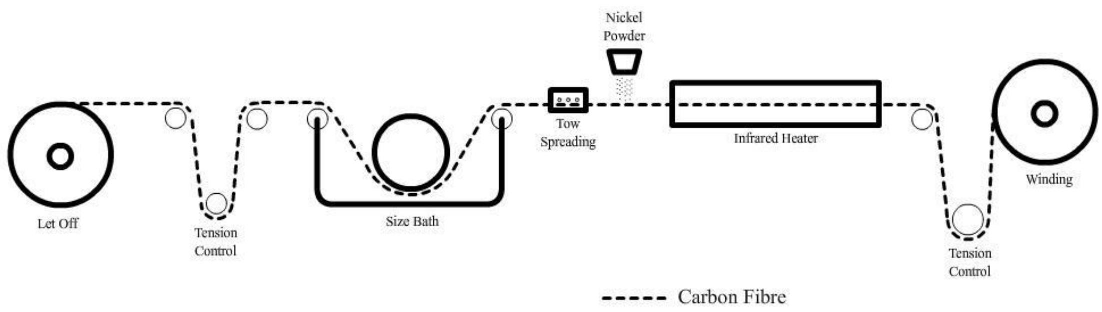

Figure 5-2 Process for coating metallic powder on the carbon tow.

Although it was possible to create a tow which is magnetisable through this method, it had the disadvantages of only applying a one grain thick metallic layer while wasting a large quantity of metallic powder. This outcome with the first method resulted in opting for the second method as seen in **Figure 5-3** for of creating metallised tow, using pre-prepared EPI-REZ^{TM} and Nickel powder to incorporate the metallic powder in the shape of a grating and this is illustrated in **Figure 5-4**.

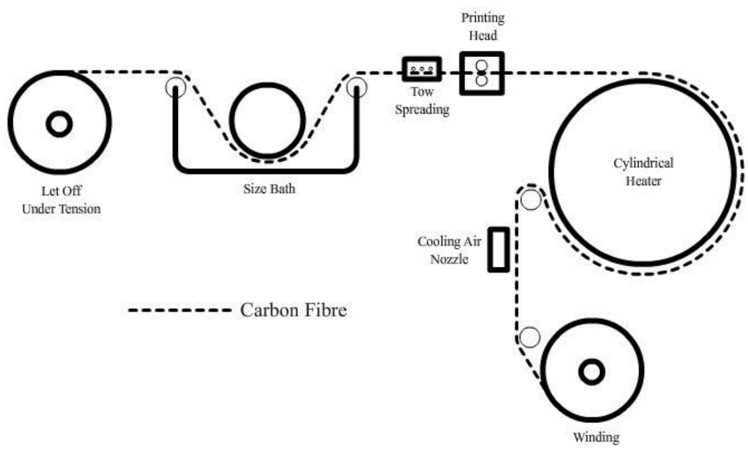

Figure 5-3 Printing of magnetic grating on the carbon tow.

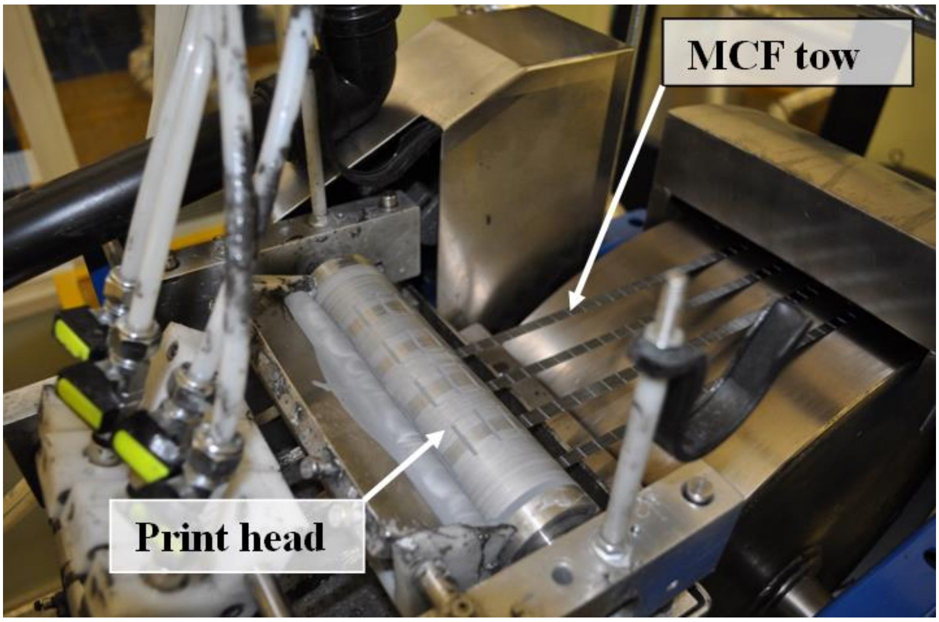

Figure 5-4 Printing Head for printing the metallic lines.

To observe the effect of the concentration of size, on the stiffness of the tow, varying quantities of size, in the steps of 0.5%, 1%, 1.5% and 2% of the weight of water was mixed in a size bath and the tow was made to run through this. In this process, through the use of air jets, the excess size was removed leaving only enough to prevent the separation of the fibres in the tow. To calculate the proportion of the sizing material in the tow, the weight of the tow was recorded. Thereafter the 12k tow samples were tested for bending rigidity using the Kawabata bending tester. Since this experiment was only to find the stiffness increase in the tow purely due to the sizing material, no metallic powder was applied to the sized tow.

In order to observe the effect of metallic powder concentrations, the first step was to create varying mixtures of nickel powder and epoxy resin. The viscosity of the original epoxy was 18,000 cP. When trying to create mixtures of epoxy powder and water for screen printing the grating patterns on to the carbon tow, it was found that 7% of water in the epoxy would give the ideal conditions. Therefore in conducting the experiments to determine the magnetic attraction due to varying proportions of epoxy and metallic powder, while keeping the weight of the epoxy constant, the metallic powder quantity was varied in steps of 20%, 30%, 40%, 50% and 60% of the weight of epoxy. To all these mixtures, a quantity of water, 7% of the weight of the epoxy, was also added. This mixture was applied on the carbon fibre tow in the form of transverse lines in a uniform pattern. Thereafter experiments were conducted to measure the magnetic attraction using a magnetic plate with a pull force of 14 kgf. The magnetic attraction force was recorded while reducing the distance between the magnet and the metallised tow.

To determine the effect of the distance between the transverse lines on the magnetic pull force, experiments were carried out for line spacing distances of 5mm, 10mm, 15mm and 20mm while keeping the line width constant. To observe the effect of the line width on the magnetic pull force, experiments were conducted for metallic line widths of 0.5mm, 1mm, 1.5mm and 2mm.

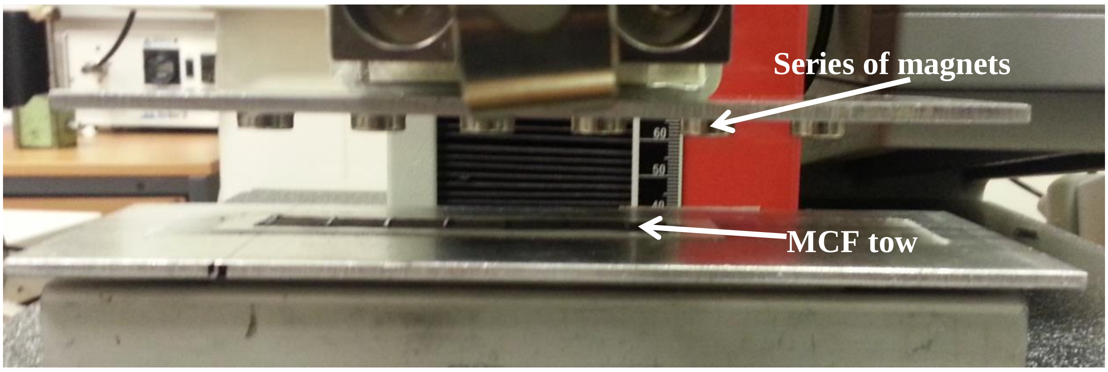

Figure 5-5 Tensile tester setup for measuring the magnetic pull force.

For all these tests to determine the effect of the metallic powder, the tow sizing was controlled at 1% to prevent filamentation, and the tensile tester was run at a speed of 5mm/min. A 25N load cell was used in the tensile tester during these tests as depicted in **Figure 5-5**.

Analysing the bending characteristics of the MCF tow and the bending energy required are important studies in understanding the process of preforming using this material. Therefore in addition to the above tests, to observe the bending properties of the MCF tow as a measure of its ability to assume the curvature of the mould used to create a preform, 3-point bending tests were carried out according to the test standard BS ISO 5620: 2012.

5.4 Results and discussion

5.4.1 Effects of sizing on the stiffness of the tow

On testing the samples having different quantities of sizing, using the three point test method, a clear increase in trend in the bending stiffness was observed for 0.5 to 1% size, as expected. There was no considerable difference in bending stiffness from 1 to 2% size.

Bending stiffness of sized tow		
Size (%)	**Bending stiffness (N.mm)**	**Bending stiffness (Standard deviation)**
0.5	1.12	0.31
1	2.99	0.52
1.5	2.84	0.20
2	2.99	0.27

Table 5-1 Bending stiffness values for varying quantities of size in the tow.

Carrying out the bending tests for a specific bending radius, as shown in **Table 5-1**, it is possible to determine the optimum sizing level for the carbon tow.

5.4.2 Effect of the metallic powder quantity on the magnetic pull force

Previous experiments conducted to observe the suitability of sprinkling for incorporating the magnetic powder in the tow has shown the inefficiency of this method. Due to this result and also due to the positive performance of the printed transverse metallic lines, line printing was adopted as the main method of metallic powder incorporation. In conducting experiments to determine the optimum quantity of metallic powder in the tow, tests were carried out for samples having a line width of 1mm and line separation of 1cm. The resulting pull force graphs are given in **Figure 5-6**.

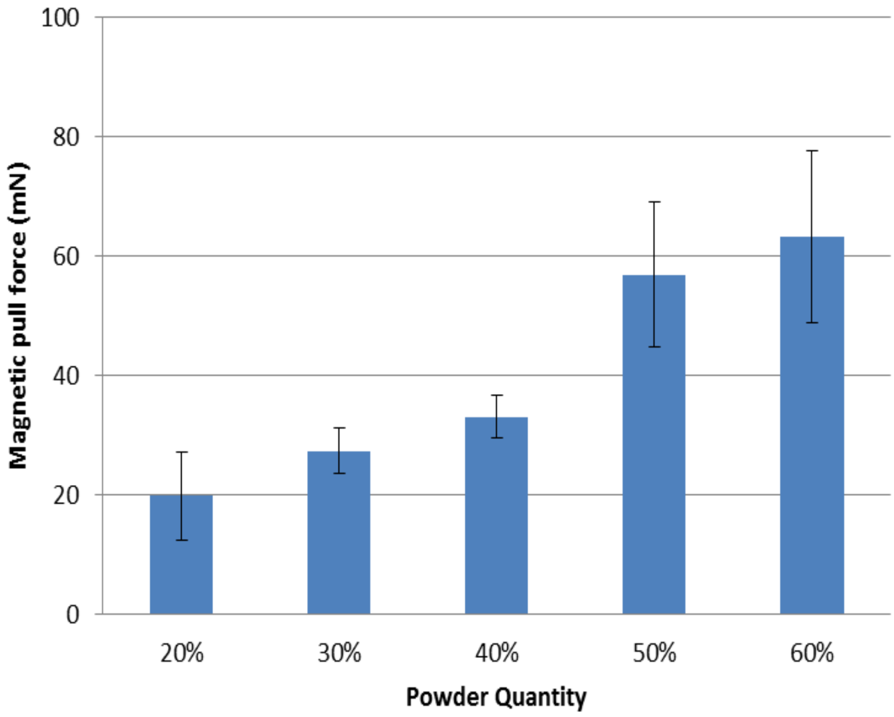

Figure 5-6 Magnetic pull force at 2mm displacement for MCF tows having varying quantities of powder.

Powder quantity	Bending stiffness (N.mm)	Bending stiffness (Standard deviation)
20%	2.56	0.72
30%	3.41	0.46
40%	3.38	0.10
50%	3.08	0.28
60%	3.19	0.54

Table 5-2 Bending stiffness of the MCF tow for varying powder concentrations

As can be seen in **Figure 5-6**, higher powder content results in a larger magnetic pull force. Also as the graph shows, the powder content is inversely proportional to the distance at which the magnetic pull is experienced. The tests indicated that for the initial approach of the magnet towards the tow, the increase in the pull force was smooth. However at a specific close separation, the tow tries to bend towards the magnet, resulting in a change of the magnetic pull force. In the current tests, MCF tow was held fast to prevent any form of displacement. Also the experiments revealed that the air gap between the tow and the magnet has a quadratic relationship with the pull force experienced. The bending stiffness of the MCF tow for various powder concentrations in the print paste is given in **Table 5-2**.

5.4.3 Effect of the metallic line spacing on the magnetic attraction

Using the results obtained by varying the metallic line spacing, it can be seen that the tow with smaller line separation is similar to having a higher quantity of metallic powder in the tow as seen in **Figure 5-7**. Therefore the behaviour of the tow is similar to that of a tow with a higher quantity of metallic powder. However rather than introducing the metal powder in a few very thick lines, it is preferred that for the DCFP process, a more even distribution of the metallic lines is provided. This will reduce the localised concentrations of weights, provide a better distribution of metallic lines in the standard chopped tow size of 2.5-7.5 cm [86, 89] and increase the adherence of the quantity of powder on the tow. It was observed that the decrease of line spacing still allowed the tow to bend in the transverse direction while maintaining a low bending stiffness. It can be seen that taller print lines promote air gaps in the moulds when the tow is finally used in the DCFP process. Therefore by increasing the number of lines for a unit tow length, the magnetic pull force is increased while maintaining the bending stiffness requirements of the tow and its thickness limitations.

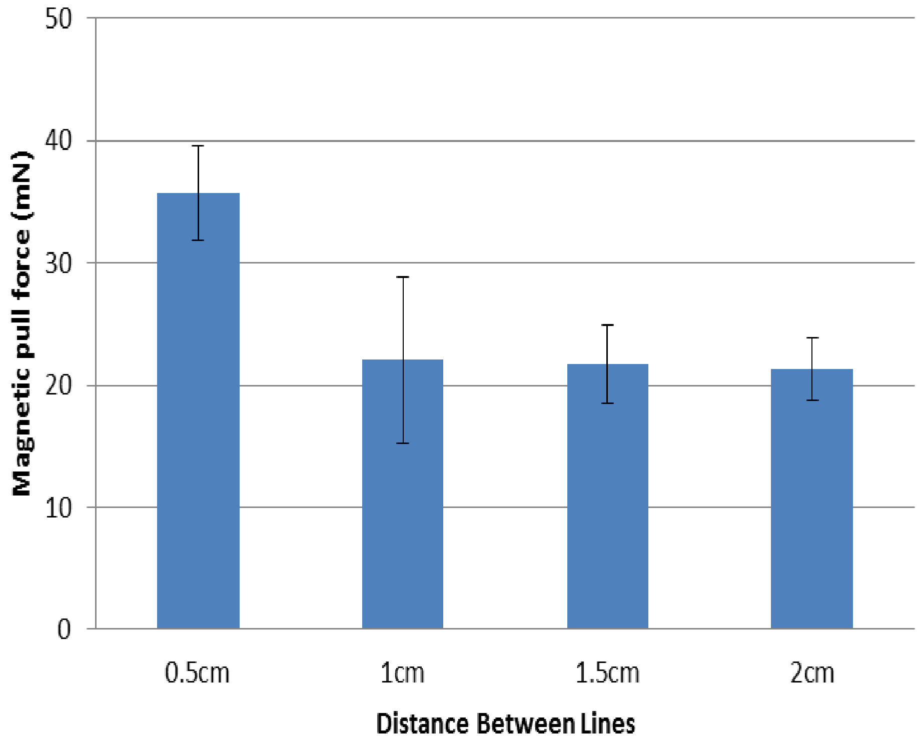

Figure 5-7 Magnetic pull force at 2mm displacement for varying metallic line separations.

Line spacing (cm)	Bending stiffness (N.mm)	Bending stiffness (Standard deviation)
0.5	5.59	1.01
1	3.44	0.25
1.5	3.65	0.43
2	1.82	0.42

Table 5-3 Bending stiffness of the MCF tow for varying printed line spaces

The results showed that for a range of line separation distances, the quadratic relationship between the air gap and the pull force was still true. The bending stiffness of the MCF tow for various print line spacings on the MCF tow is given in the **Table 5-3**.

5.4.4 Effect of the metallic line width on the magnetic attraction

As in the above cases, increasing the metallic line width has the effect of increasing the quantity of metallic powder incorporated into the tow. Therefore change was observed as confirmed in **Figure 5-8** in the relationship between the air gap and the pull force. Also the change in the MCF bending stiffness due to varying the printed line width is given in the **Table 5-4**.

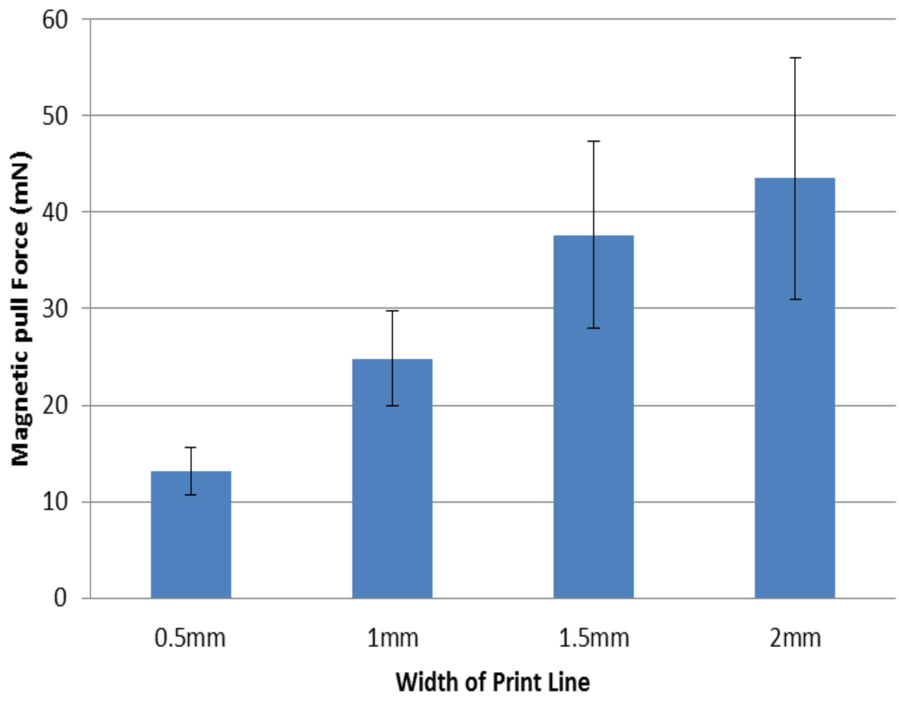

Figure 5-8 Magnetic pull force at 2mm displacement for varying metallic line widths.

Line width	Bending stiffness (N.mm)	Bending stiffness (Standard deviation)
0.5mm	2.74	0.45
1mm	2.86	0.32
1.5mm	3.52	0.68
2mm	2.45	0.66

Table 5-4 Bending stiffness of the MCF tow for varying printed line width

It can be understood that as long as the metallic line deposition width is maintained as a fine line, the capability of the MCF tow to assume any curvature of the mould is not impeded. However on increasing the line width, since the bending stiffness of the print line itself is high, the tow will not conform to smaller radii.

During the experiments it was observed that if the excess size was not mechanically removed, the sizing has the tendency to mix with the epoxy/nickel powder paste and diffuse around the print line. Also if the print paste layer on the print head as depicted in **Figure 5-4** is not wiped clean, it can introduce epoxy and metallic powder throughout the tow. This will result in increasing the stiffness of the tow and introducing metallic powder randomly onto the tow. Since this is an undesirable outcome, so during printing metallic lines on the tow, every precaution was taken to ensure that the exact predetermined paste quantity was printed.

5.5 Conclusion

Size is a main component of the MCF tow which binds the carbon fibres together. In engineering the metallised tow first the size quantity is decided to obtain the minimum stiffness for conforming to the smallest mould radii. This relationship can also be represented by the variation in the bending stiffness due to the change in size quantity used. The size quantity that can be used, again, is limited since overuse of it would result in the dissolving of the metal epoxy paste and its diffusion along the tow. Another important factor which affects the bending stiffness is the distance between the print lines. The variation of powder percentage in each print line and width of each print line had no major effect on bending stiffness properties. Therefore using the graph of bending stiffness vs. size quantity and bending stiffness vs. line distance, it is possible to determine the size quantity and line spacing required to achieve a specific bending stiffness for the 12k carbon tow.

The tests to measure the magnetic pull force between the MCF tow and the permanent magnet describes a relationship similar to that defined in equation 3. All the experiments to measure the magnetic pull force shows that whatever way the metallic powder is introduced, the magnetic pull force can be increased. However this has to be carried out so that the low bending stiffness of the MCF tow is preserved. Metallic lines are introduced at required line separation and line width. Again having the minimum printable line width is advantageous. Also it was seen that if the lines were printed too close together, they tend to merge together, increasing the stiffness of the tow. Therefore the tests conducted show that in this particular case a metallic line width of 1mm, a line separation of 10mm, 1% size quantity and 40% quantity of metallic powder is most appropriate. The percentage weight increase of this tow is 11% compared to that of raw tow. This weight of the tow can also be varied according to the requirements by changing the powder percentage, line distance and line spacing.

The purpose of applying metallic lines is that once the chopped tow pieces are placed on the mould to a specific thickness, the magnetic field of the mould will be capable of compacting the chopped tows against the mould surface. From **Figure 5-6, Figure 5-7** and **Figure 5-8**, it can be deduced that for the present case a maximum of 7 mm composite thickness could be constructed using the magnetic field used in the experiments. However, by increasing the strength of the magnetic field, it is possible to increase the composite thickness.

Acknowledgements

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References

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Chapter 6. Carbon/cobalt co-mingled tow for directed carbon fibre composites

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6.1 Abstract

Directed Fibre Preforming (P4) is a novel composite manufacturing process first introduced by Owens Corning in Battice, Belgium and Aplicator systems AB, Sweden. Directed Carbon Fibre Preforming (DCFP), which is a derivative of P4, uses carbon fibre tow as the main engineering raw material for manufacturing carbon based composites for automotive and aerospace applications. Depending on the method by which the carbon fibre tow is presented to the mould surface, the preforming process uses either positive air flow or metallised carbon fibre tow to ensure fibre conformance to the 3D mould surface geometry. The research work presented in this paper (continuation of paper- 1 and 2) investigates the use of carbon/cobalt co-mingled tow as a possible candidate for the type of metallised carbon fibre tow. The paper describes the mechanical and magnetic properties of such co-mingled tow and investigates its suitability to be used as a raw material in the DCFP process.

Keywords: Cobalt wire, Carbon Fibre, Metallised, Magnetic, Preforming, DCFP

6.2 Introduction

In the moulding of vehicle components using carbon tow, due to mechanical properties desired from the finished component, flat tow carbon preforms are much preferred[95]. Since the innovation introduced in the current research is the creation of metallised carbon tow, the ferromagnetic carbon tow that is produced needs to be of flat and thin cross-section to support tow bending and higher fibre volume fraction. In the present research, the ferromagnetism is introduced by combining cobalt microfilaments together with the carbon fibres. Since the load bearing member in this composite tow is the carbon fibres, the selection of the suitable cobalt microfilaments is only decided by the stiffness of a cobalt microfilament, the viscosity of the epoxy that would be needed to incorporate the cobalt microfilaments into the carbon tow and the relative ease of the method used to combine the cobalt microfilament to the carbon tow. Although it is possible to deposit chopped cobalt fibres in a transverse direction, in the correct density, to achieve the required ferromagnetic metallisation, practically, it would be a more cumbersome process compared to a simple co-mingling process. Previous studies show [96-107] that extensive effort has gone into the manufacturing of various types of co-mingled yarn, their use in composites and the analysis of their relative advantages for using co-mingled yarn in the composites and the effect consolidation and impregnation have on the composite processing. Therefore as long as the co-mingled carbon/cobalt fibres used have the optimum stiffness and tow integrity that does not hamper the minimum bending radii expected from the metallised carbon tow, commingling is a perfectly viable metallisation process. At the same time, to fulfil the primary objective of the metallised carbon tow, the optimum cobalt fibre density required for the DCFP process also needs to be determined. To obtain this information, both theoretical and experimental approaches can be used. At the same time by observing the magnetic field strength required to separate the cobalt filaments from the co-mingled tow, the component integrity of the co-mingled tow can be determined.

The mechanical properties of the co-mingled yarn are decided by the demands of the engineering application. Therefore, the co-mingled tow needs to be capable of maintaining its cross sectional shape while having low flexural rigidity in the lengthwise direction. Since lower bending rigidity in the transverse direction can ultimately result in tow splitting and fibre separation, the width of the tow needs to be controlled. The narrow width is again an advantage when the tow conforms to a curvature perpendicular to the tow longitudinal direction. Additionally, the use of the optimum sizing viscosity is essential to prevent/ reduce the fibre separation, critically in the case of the cobalt microfilament. Therefore to obtain a flexible co-mingled tow with an optimum attraction to a magnetic field with a minimum of cobalt microfilament separation and tow splitting; tow samples need to be manufactured and tested for a range of epoxy size viscosities and filament numbers.

The experiments for determining the magnetic attraction between the cylindrical disc magnets and the carbon tow mingled with 1-5 cobalt wires of 20 micron diameter were designed to use neodymium permanent disc magnets. Neodymium magnet is apermant maget made from an alloy of neodymium, boron and iron to form tetragonal crystalline structure ($Nd_2Fe_{14}B$). The basic theoretical relationships that govern the pull force (F) at a distance 'x' can be given by the equation below [90, 91]:

$$F = A\frac{\left[\frac{B_r}{2}\left[\frac{L+x}{\sqrt{R^2+(L+x)^2}}-\frac{x}{\sqrt{R^2+x^2}}\right]\right]^2}{2\mu_0\mu_r} \text{-------} \textbf{(1)}$$

where

F = magnetic pull force

A = area of the magnetic flux

μ_0 = magnetic permeability of free space

μ_r = relative magnetic permeability

B_r = remanence of the magnetic material

L = thickness of the magnet

R = radius of the disc magnet

x = distance from the magnet

The theoretical relationship between the magnetic pull force on the cobalt wire and the distance to it from the disc magnet is plotted in **Figure 6-1**. As seen in the graph, the distance between the magnet and the cobalt wire has an inverse relationship of a higher order with the magnetic pull force. Due to the fine dimensions of the cobalt wire, the magnetic force it experiences is in the region of millinewtons (mN).

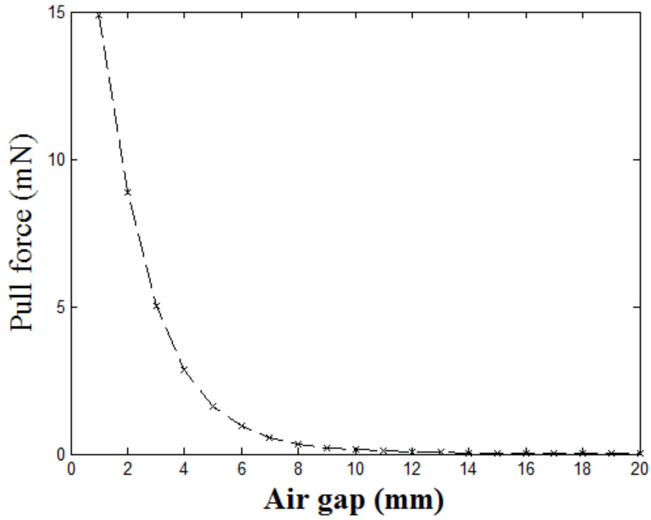

Figure 6-1 Theoretical relationship of pull force and air gap distance for a neodymium magnet and a cobalt wire

6.3 Experimental Methodology

For engineering applications, unidirectionality and the continuity of the carbon fibres in tows is preferred primarily due to load bearing requirements. The presence of damaged or twisted carbon fibres that could arise from the carbon tow manufacturing process would make it either unsuitable or of poor quality for load bearing applications [107]. Therefore, any fibre processing method that could compromise the strength of the tow cannot be used to combine the cobalt filament with the carbon. This limitation rules out the use of spinning methods to combine the cobalt filament with the carbon filaments. Therefore a tow sizing machine that can process the carbon fibres unidirectionally, while allowing the cobalt filaments to combine with the carbon fibres, was built. The machine was built with the capability to set the co-mingled tow shape through heat curing, once the mingling and sizing of the fibres are carried out.

Ferromagnetic cobalt microfilaments can be combined with a bundle of carbon fibres using plying or merging techniques and through subsequent epoxy sizing [20]. However, since for the present application tow spreading is essential, fibre merging was used to combine the cobalt fibres together with the carbon fibres to produce a metallised carbon tow. **Figure 6-2** shows the process setup that was used for combining the cobalt microfilaments with the carbon tow using water based epoxy resin (EPI-REZ™ from Hexion) as the sizing material.

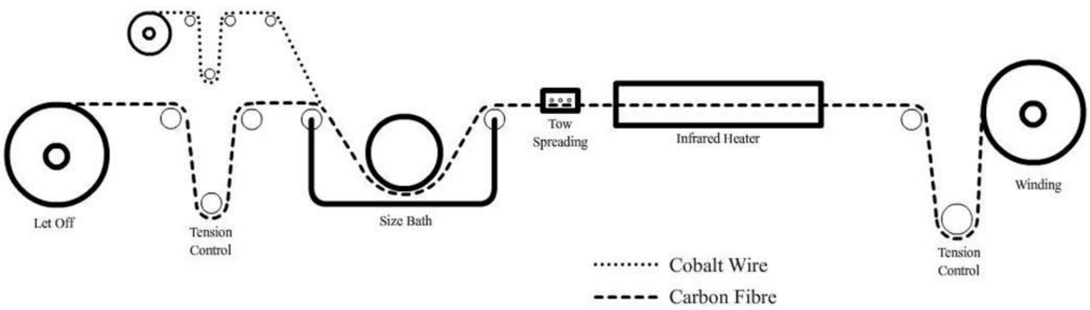

Figure 6-2 Manufacturing process for combining cobalt microfilament with a carbon tow

The major stages in the tow processing in creating the co-mingled carbon/cobalt tow are shown in the **Figure 6-3**, **Figure 6-4**, **Figure 6-5**, **Figure 6-6** and **Figure 6-7**.

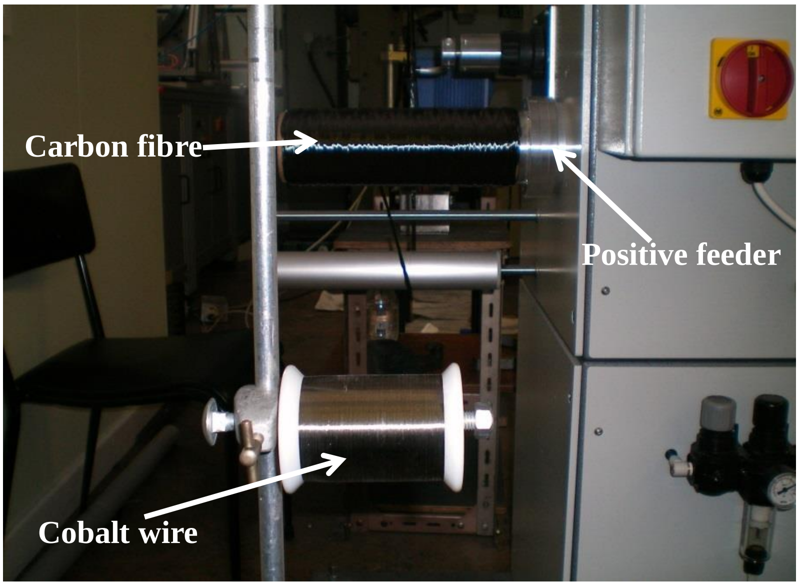

Figure 6-3 Carbon Tow and Cobalt wire letting off under tension

As shown in **Figure 6-3**, unwinding of the carbon tow from the bobbin is handled by a tension controlled positive feeder, that incorporates a compensator arm. Since it was found that matching the feed rates and the tensions, in the carbon tow and the cobalt wire at the same time is difficult, the cobalt package was placed on a spindle for the carbon to pull on demand.

Here, to maintain a comparable tension in the tow and the filaments, both the carbon tow and the cobalt wire were threaded through the same tension controlling arm in the feeder mechanism where they were brought together.

The mingled dry filaments coming from the letting off stage were next passed through a water based epoxy size bath as shown in **Figure 6-4** to infuse the resin required to bond the carbon fibres and the cobalt filaments together. Due to the take-up of the epoxy size, the mingled tow that leaves the size bath forms a tow with a circular cross section. To ensure a uniform consistency in the bath, a method of stirring was incorporated in to the size bath.

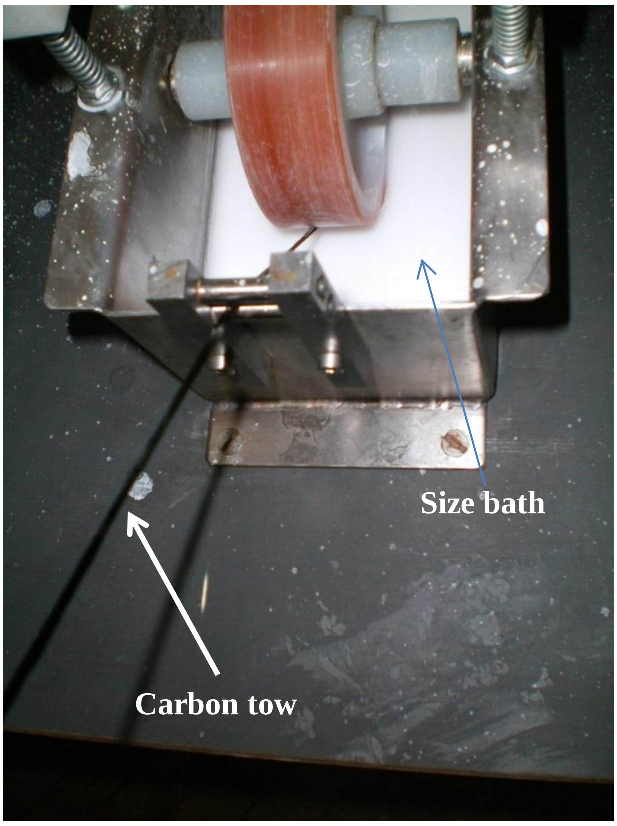

Figure 6-4 Size bath

For using the co-mingled carbon tow, for moulding over smaller radii, its flexural rigidity needs to be within acceptable limits. In addition to the stiffness of the component materials, the flexural rigidity in this case is influenced by the cross sectional dimensions of the co-mingled tow. It was found that tensioning the tow over a cylindrical shaft, in this case, was insufficient to achieve the 12mm width requirement dictated by the DCFP process using the 12k tow material used throughout the research.

Therefore to achieve a better spread of the tow, the tow was passed along a shaft with a convex shape. As can be seen in the **Figure 6-5**, the round cross-section tow can be seen to move along a convex shape to cause the carbon tow to spread to a flat shape. Different roller radii were tried before finally arriving at the optimum roller radius. It was found that at too high a radius, the tow tracks to one side of the roller or tow splitting takes place. It was found that better results in spreading are achieved when the shaft used in this case is stationary rather than rotating.

Figure 6-5 Spreading rollers

The tow-convex roller interface was continuously kept moist due to the excess epoxy size in the tow. Control of the tow tension in this stage was found to be important to prevent tow splitting since too high a tension tends to split the spread tow. These limitations in turn decide the minimum tow thickness that can be achieved in this process arrangement of tow spreading. During this stage, the excess epoxy size in the tow was removed using an air jet, in order to reduce the flexural rigidity of the tow and the viscous friction.

The flat tow leaving the spreading stage was next fed against an infrared heater as shown in **Figure 6-6** heated to 110^{0}C at a speed of 2 to 3 m/min. Since the work involved was exploratory, no priority was given to increasing the tow processing speed.

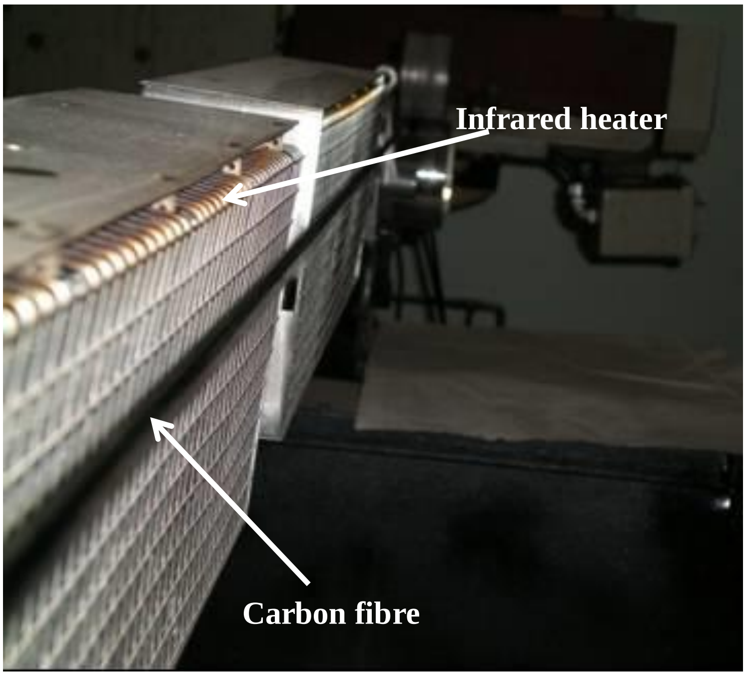

Figure 6-6 Infrared Heaters

Again it was found that the bottleneck for the tow speed is the rate of curing at the infrared heater. Therefore it was noted that for any further process development which involves curing of carbon tow having water based epoxy resin, a more efficient curing method, such as contact heating, is necessary. During this stage the tow was found to contract slightly due to evaporation of the moisture in the epoxy resin. The subsequent cooling in the present case was carried out at room temperature in natural air. It was noted that for an efficient system that carries out metal wire mingling with carbon tow, the process would need facilities for active cooling.

Figure 6-7 Winding

Finally, the dry tow leaving the curing stage was wound on to a package using normal cross winding as shown in **Figure 6-7**. However, it was found that this method is not the optimum process for winding flat tapes since the reciprocating eyelet tends to crush the flat tow causing it to split and fold over.

To determine the quality of integration of the cobalt wires in the carbon tow, the tow prepared as described above together with the commingled cobalt wire was tested for mechanical and magnetic properties using the three point bending stiffness tester and the Zwick tensile tester. Since the flexural rigidity of the epoxy sized cobalt co-mingled carbon tow is an important measure for subsequent processing of the tow in manufacturing, the three point bending tester was used to measure the bending stiffness for various epoxy size concentrations. Here the samples were cut and mounted in the three point bend tester, according to the standard BS ISO 5628:2012. The effect of the viscosity of the epoxy size on the bending stiffness of the tow, arrived at using the three point bend tester results, is given in the results and discussion section.

To determine the magnetic attraction achieved through the inclusion of cobalt wires in the carbon tow, the tow was tested for magnetic attraction using a tensile tester. To carry this out, an array of 10 mm diameter and 10 mm thick neodymium permanent magnets (6 magnets) were held on the cross head of the tensile tester. While holding co-mingled tow samples of 100 mm length stationary, parallel to the cross head, the magnet array was lowered at 5 mm/min. This experiment was conducted for co-mingled tows having one to five wires of cobalt of 20 micron diameter. The resulting observations of the load cell reading against the crosshead position was used to determine the magnetic attraction of the co-mingled tow.

6.4 Results and discussion

Although the co-mingling of the cobalt was carried out with relative ease, it was observed that the bond strength provided by the epoxy size between the carbon tow and the cobalt wire was quite weak. This resulted in difficulties of maintaining the integrity of the co-mingled tow during handling and tow cutting. It was noticed that, even though, by increasing the viscosity of the epoxy size, the bond strength can be increased; this would adversely affect the flexibility of the co-mingled tow as graphed in **Figure 6-8**. Also as can be seen in **Figure 6-8**, the stiffening effect of the cobalt wire was apparent only when the epoxy size concentration is greater than 1.5%.

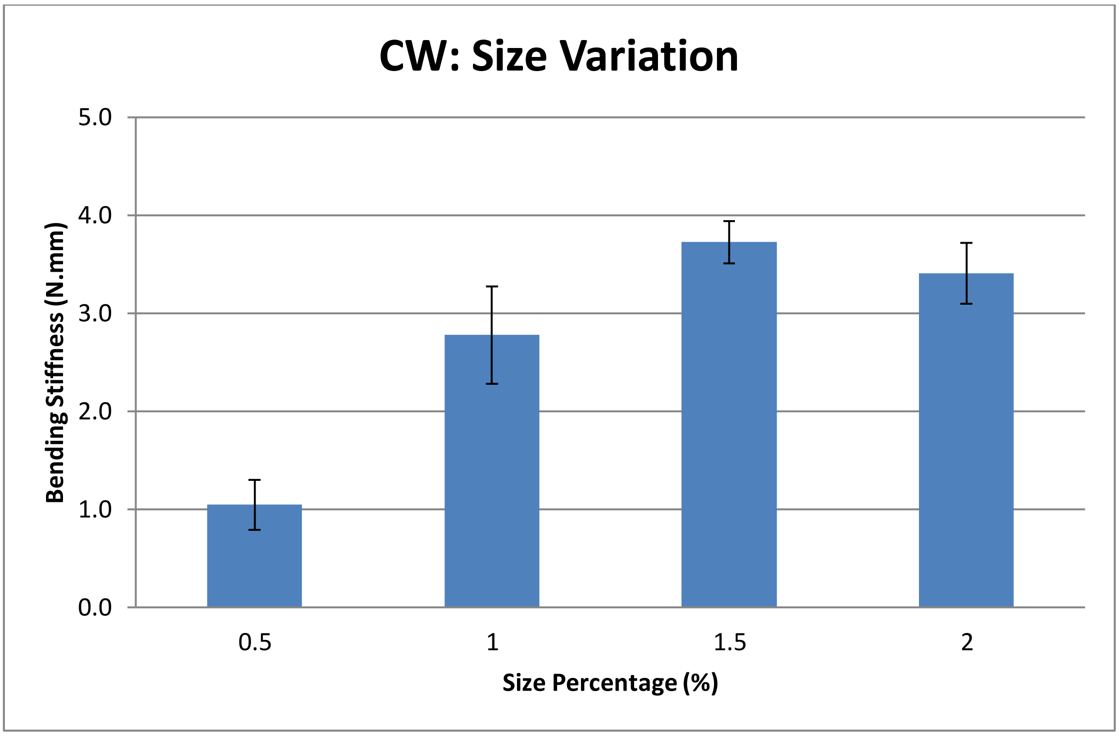

Figure 6-8 Bending stiffness of carbon tow and carbon/cobalt co-mingled tow for various epoxy concentrations

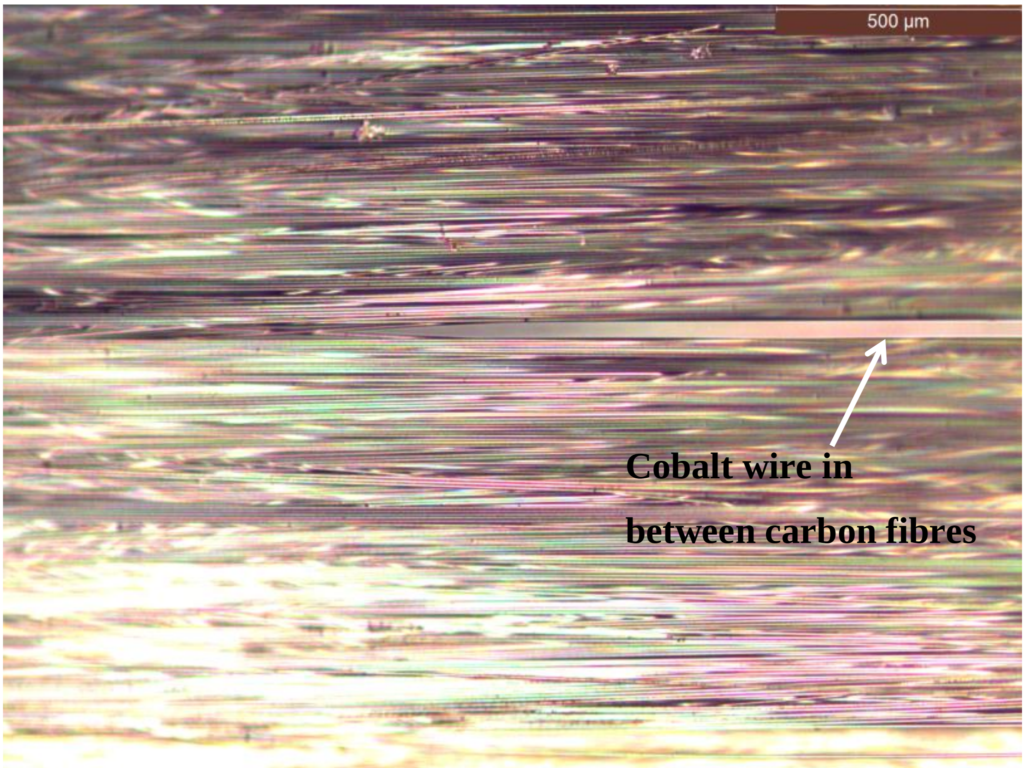

Figure 6-9 Optical microscope image of the co-mingled cobalt in the carbon tow

It was observed that at low epoxy viscosities, the cobalt wire together with the carbon fibres had a greater freedom of movement, thereby reducing the bending stiffness of the tow. However at higher concentrations, the fibres of tow were held permanently by the size thereby converting the co-mingled tow to a stiff band. As can be seen in **Figure 6-9**, precise positioning of the cobalt wire within the carbon tow is a difficult process. As seen, the wire can be either within the tow or on the surface of the tow, thereby giving different tow properties.

To observe the magnetic force between the co-mingled tow and a magnetic field and also to determine the quantity of cobalt wires necessary for achieving a high enough magnetic pull force suitable for DCFP processing, a graph giving the magnetic pull force vs. the air gap relationship between the cobalt wire and the magnet was plotted for different wire densities as seen in **Figure 6-10**.

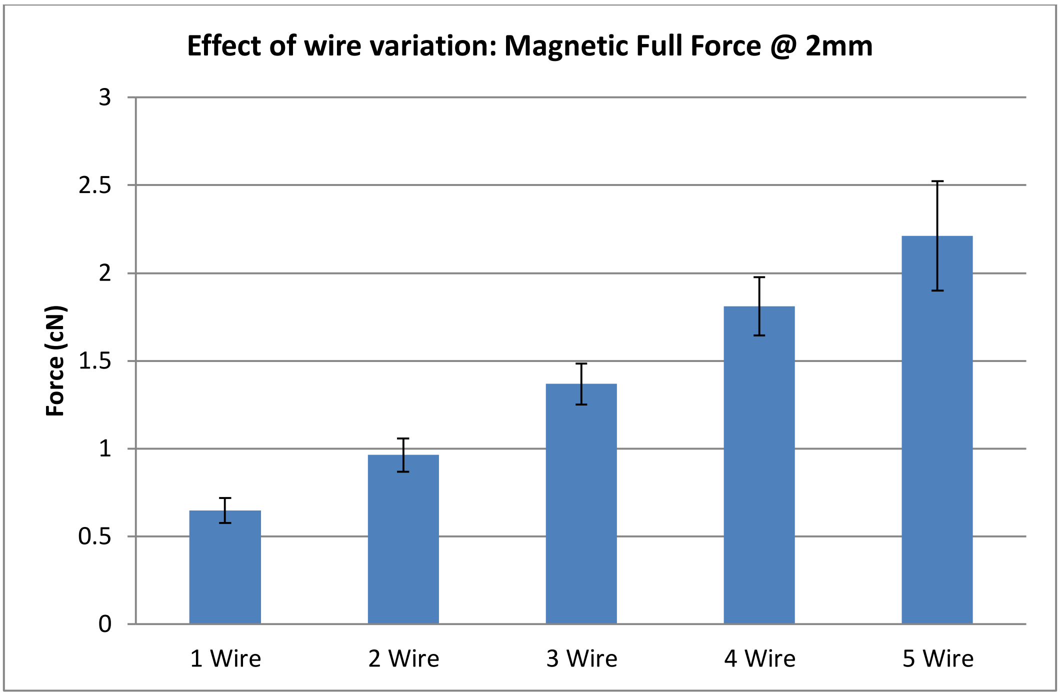

Figure 6-10 The graph of magnetic pull force on the co-mingled carbon tow experimental data

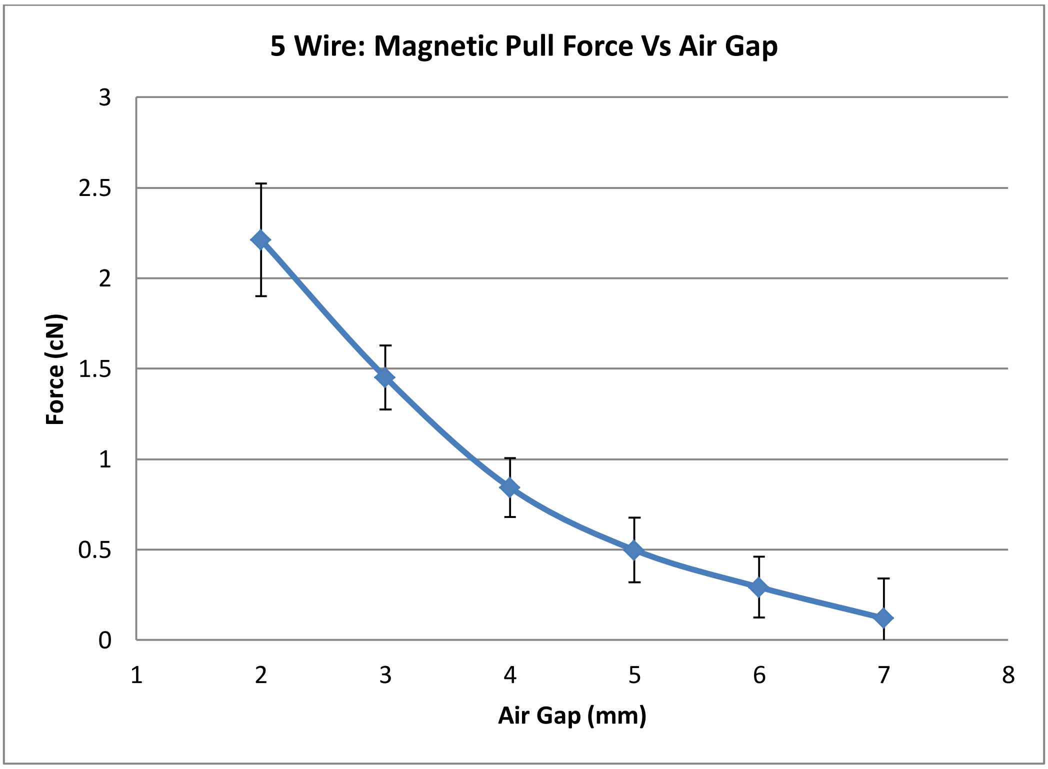

Figure 6-11 The graph of distance vs. air gap for 5 cobalt wire /carbon co-mingled tow.

As seen in **Figure 6-10**, the general relationship of the increase of the magnetic pull force on the introduction of a higher wire density and the inverse relationship between the air gap distance and the magnetic pull force can be seen to prevail. However as seen here, at a distance of 10 mm, the magnetic pull force is negligible, as shown in **Figure 6-11**. The static magnetic field created by the six magnet array was modelled using Ansys finite element modelling, to visualise the magnetic attraction and the magnetic field, shown in **Figure 6-12**.

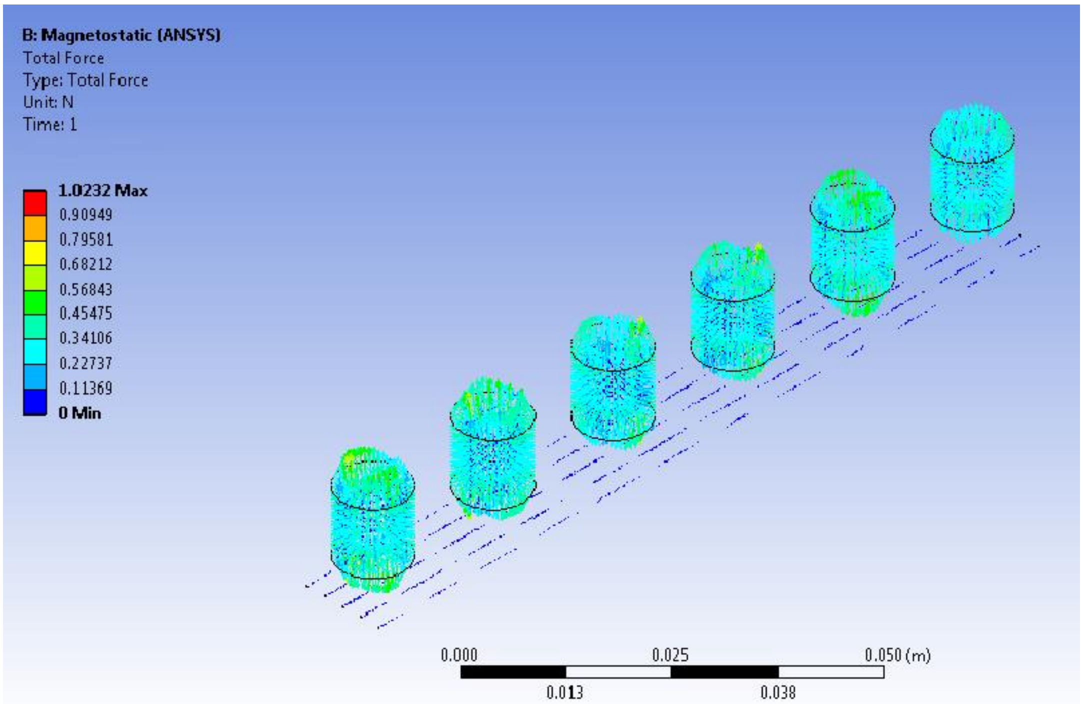

Figure 6-12 Magnetic force experienced by the cobalt wire

6.5 Conclusions

This method of MCF tow manufacturing uses epoxy size in order to bond the cobalt wire on to the spread carbon tow. As was observed, the quantity of epoxy determines the strength of adhesion between the commingled tow. It was observed from the bending stiffness testing using the three point bend method that as the size quantity increased, bending stiffness had also increased. From the magnetic pull force experiment it can be seen that as the number of cobalt wires increases, magnetic pull force had also increased. As the distance between the magnet and the wire increased the magnetic pull force decreased.

From **Figure 6-11** it can be deduced that the present mould thickness maybe up to a maximum of 7mm. For a particular mould surface it is possible to systematically engineer the carbon fibre and cobalt wire co-mingled tow.

Acknowledgements

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References

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Chapter 7. Measurement of carbon tow bending stiffness using different test methods

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7.1 Abstract

The increased use of composites in industry has resulted in increased use of finite element analysis software to predict the properties of composites. In order to predict the properties of a composite preform using finite element analysis requires a major input parameter, which is Bending Stiffness.

Most of the bending stiffness test methods were developed for garments and composites. However in this paper Bending Stiffness of Carbon Tow and MCF (metallised carbon tow) are investigated using various methods such as Cantilever, KES (Kawabata Evaluation System), 2 point and 3 point bend test methods. The experimental results of bending rigidity from the various tests are analysed, and a mathematical deflection model is derived. Finally, ideal methods to identify the bending stiffness of the carbon tow are presented.

Keywords: Bending rigidity, Metallised, Carbon fibre, Tape

7.2 Introduction

The use of carbon fibre composites has increased in aeroplanes, fuel cells and automobiles due to its strength/stiffness to weight ratio, durability and corrosion properties [108]. Finite element analysis is an important tool to predict the properties of the composites before making the actual product, which in turn saves time, money and avoids modelling of individual fibres (12K) that is computationally expensive[92].

Bending stiffness is a major input parameter in the modelling software, as it relates to bending the tow along the curvature of the mould surface during preforming. Also Bending Stiffness is an important factor in fabric formability and automation [109-112]. Furthermore, Bending resistance of the fibres in the bending direction, interaction between fibres and frictional resistance determine the bending properties[113]. Also during the preforming process the preform undergoes in-plane and out-of-plane deformations[114]. Flexural rigidity is also known as bending stiffness and measures the actual force produced during the bending of the material i.e. the resistance to bending[115].

There are several test methods (British standards and ASTM standards) available for finding the bending stiffness of textile garments and composites but there are no standards available for finding the bending stiffness of multifilament carbon tow. The bending stiffness of MCF tow is an important factor in bending the tow along the curvature of the mould surface during the chopped fibre deposition process [116].

This research focuses on the various test methods that are available to measure the bending stiffness. Bending stiffness testing techniques can be divided into two main categories. In the first category the carbon tow deforms under its own weight and in the second category carbon tow deforms under external force[109]. The cantilever bending test using the Shirley tester belongs to the first group in which the tow bends by its own weight, this system is also called FAST (Fabric assurance by simple testing). In this system the deformation is measured at a single point. Whilst in the KES-FB (Kawabata evaluation system), 2 point and 3 point test methods the deformation behaviour of the tow over a certain length is measured.

KES is most widely used in the case of pure fabric bending i.e. neglecting the effect of shear deformation on the deflection[117]. There are several research papers available comparing the results of Kawabata and Cantilever Shirley tests for fabric, and they have found that results of both tests had good correlations, even though there is significant difference in the test principles [113, 118-121].

The aim of this research was to find the bending stiffness of the carbon tow using both the principles, one in which the tow bend under its own weight, and secondly, by the application of external force. The results are then compared.

Processed/MCF and raw tow were used in this experiment to find the bending stiffness and to observe the difference in results. An intermitted metal line was printed on to one surface of the spread carbon tow and the bending stiffness was found by bending the tow in both the directions. When the carbon tow is under deformation, one surface is subjected to tension and the other to compression. Therefore depending on the direction of deformation the print line surface comes under compression or tension. For each bending test method the results for raw tow are compared with printed tow deformation along compression and along the tension surfaces as shown in **Figure 7-1**.

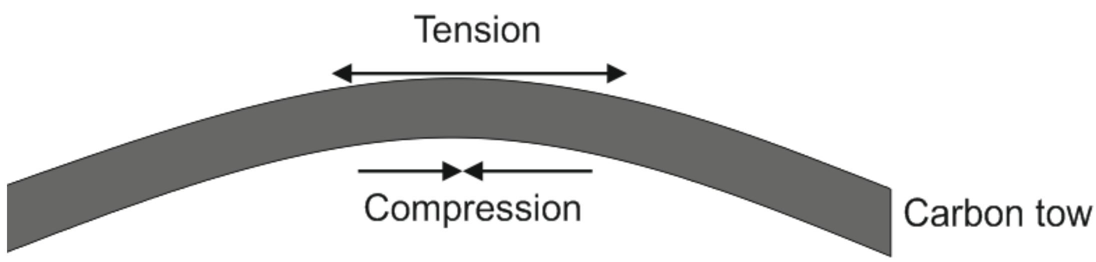

Figure 7-1 Bending of carbon tow

7.3 Experimental

7.3.1 Material

Metallised carbon tow as depicted in **Figure 7-2** was made by spreading the carbon tow to the required width, then it was intermittently printed with lined of epoxy nickel paste [59]. The printed tow was then heat cured using a cylindrical heater, cooled and finally flat wound onto a bobbin. The carbon tow used for his research was Toray T700 12K with a linear density of 800 Tex and fibre diameter of 7 microns. The ferromagnetic material used for this experiment was nickel powder Type 123 and the epoxy resin used to bond the ferromagnetic material onto the carbon tow was water-based epoxy EPI-REZ^{TM} from Hexion.

All the tests were performed under standard conditions i.e. temperature 20±2^{0}C and humidity 65 ±5%.

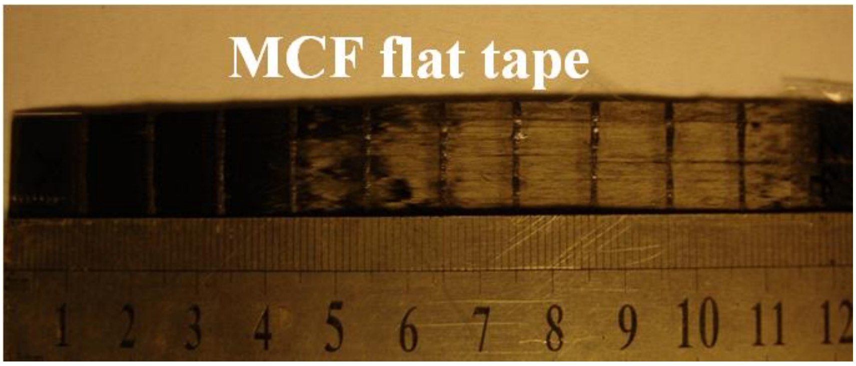

Figure 7-2 Metallised carbon fibre tow

7.3.2 Cantilever test bend test method

The Shirley cantilever test is one of the popular commercially used tests to find the bending rigidity of textile fabrics [122, 123]. In the Shirley cantilever test the tow bends under its own weight to a known angle of 41.5^0 and the bending length is measured - which is half the cantilever length. The standard states that the width of the specimen must be of 25±1mm; in this research the width of the specimen was the width of one carbon tow which is ~10mm. This technique determines the deformation level at a single point on the deformation curve. The cost of this equipment is considerably lower compared to other bending rigidity measuring devices such as Kawabata and the tensile testers used for 2 point and a 3 point testing [124].

In this test a rectangular carbon tow was placed on a horizontal platform, which is extended in a lengthwise direction over the edge of the platform. The tow is bent by its own weight, and when the angle of bending reaches 41.5^0 then the bending length is measured. This test was performed according to the British standard 3356:1990 as seen in **Figure 7-3**.

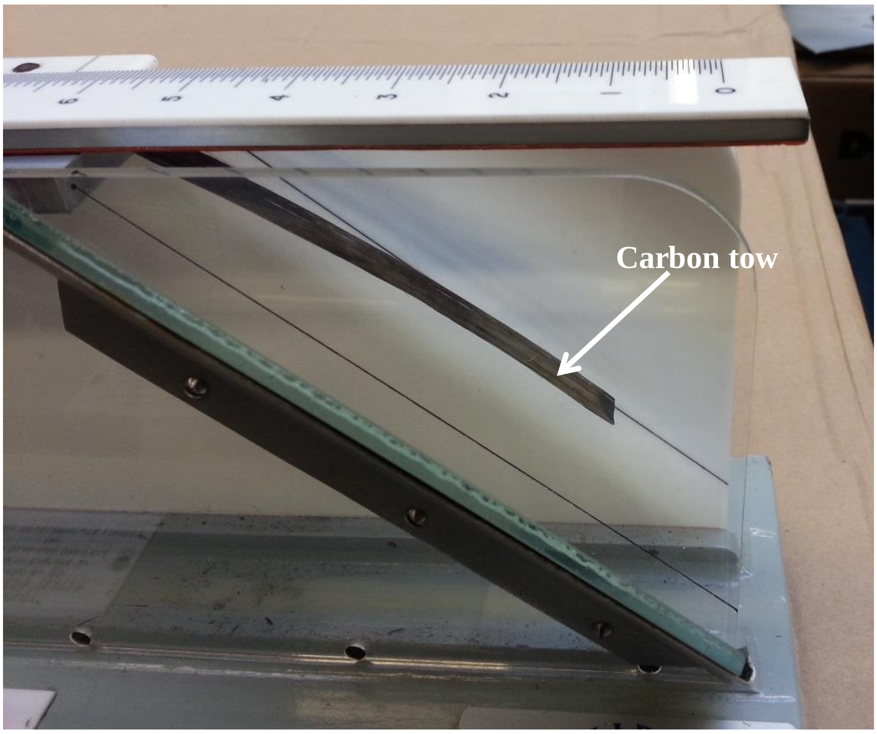

Figure 7-3 Shirley cantilever bend tester

The bending rigidity was found using the equation G= 0.10 MC^3 , where G is the bending rigidity (mg.cm), M is the mass per unit area (g/m^2) and C is the bending length (cm). According to the British standard 3356:1990 the bending rigidity unit is mg.cm this is converted to N.mm for comparing the results with the bending stiffness values from Kawabata bending test, 2 point bending test and 3 point bending test.

7.3.3 2 point and 3 point bending test methods

In the case of 2 point cantilever and 3 point test methods the weight of the tow was not a major factor as the tow is bent to a known distance under the application of external force. These tests are extensively used to find the bending stiffness of resin infused tow;

in this case they were used to identify the bending stiffness of a single carbon tow and the resulting bending stiffness values were compared to those of other test methods like Kawabata and the Shirley cantilever tester. The width of the single tow was incorporated into the bending stiffness equation. Bending stiffness was found by multiplying the modulus of elasticity and the second moment of inertia, which is then divided by the width of the specimen, represented in the following equations.

$$S_b = \frac{E.I}{b}$$

$$S_b = \frac{F}{f} \times \frac{l^3}{3b}$$

In the equation, F is the force in Newton, f is the linear deflection in mm, l is the bending length in mm, b is the width of the specimen and Sb is the bending stiffness in N.mm.

Bending stiffness in the case of two point and three point test methods is represented as f_{max} and is calculated using the equation, from the maximum slope of the curve from the force(N) versus linear deflection(mm) as shown in **Figure 7-4**.

$f_{max} = 0.132l$

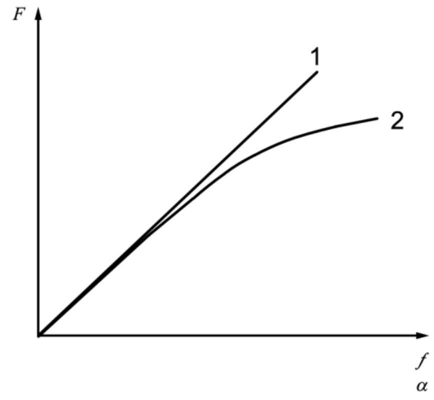

Figure 7-4 Force versus angular deflection for 2 point and 3 point bend methods (BS ISO 5628: 2012)

Bending stiffness was found by applying an external force and recoding the linear deflection in both the two point and three point methods as per the British standard BS ISO 5628:2012.

In the three point method the specimen is placed on two anvils and force is applied downwards in the centre of the specimen, then the deflection is measured as illustrated in **Figure 4-9**.

In the two point bending method the specimen is clamped at one end and a force F is applied on the opposite end at a distance l. f is the linear deflection, and was measured by the displacement at the point of application of force as seen in **Figure 7-5**.

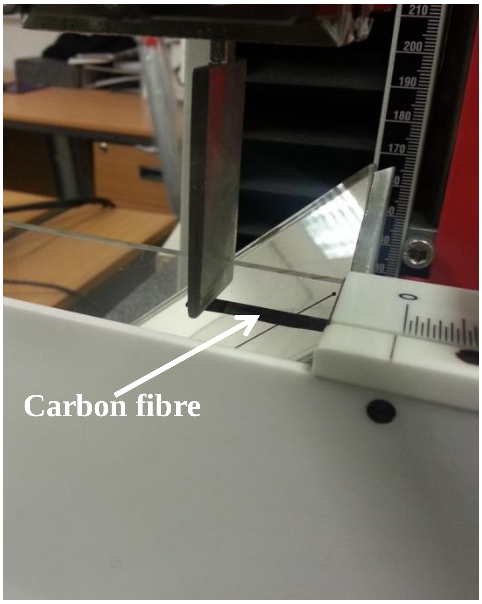

Figure 7-5 Two-point testing method

7.3.4 Kawabata bend test method

In the Kawabata system, load was applied on the specimen and the moment producing deformation is measured as shown by the curve in **Figure 7-7**. This system applies the principles of pure bending in which the tow is bent in an arc of constant curvature which converges constantly[125]. The bending properties are nonlinear due to inter-fibre friction [126]. The cost of this equipment is considerably higher than that of the Shirley cantilever tester, but is widely used for measuring fabric rigidity. The width of the specimen used in this experiment is the width of the single carbon tow.

In this experiment using the Kawabata bending tester, carbon tow is bent in an arc of constant curvature which changes constantly with the distance between the chucks at 1cm. Bending rigidity was calculated from the initial slope of the moment/curvature curve as shown in **Figure 7-7**, which was obtained using the Kawabata tester illustrated in **Figure 7-6**. In the Kawabata bending tester the chuck A is fixed and chuck B moves at a constant rate bending the carbon tow to a uniform curvature of 2.5cm^{-1} at a rate of 0.5 cm^{-1}/sec.

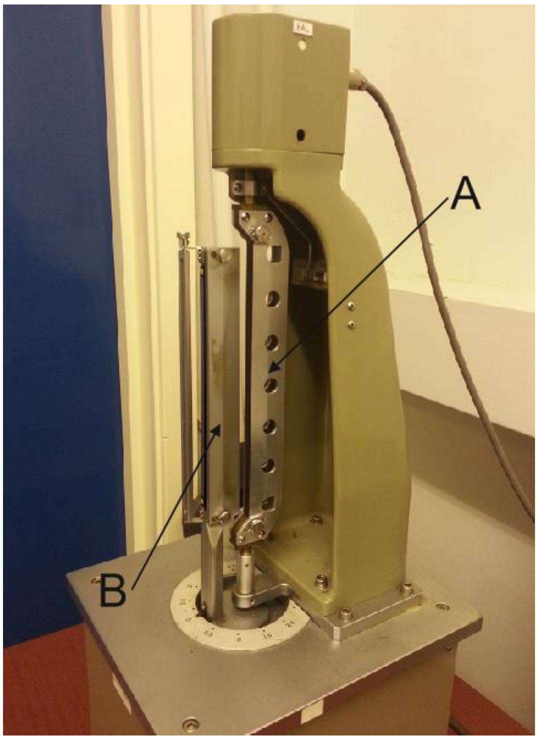

Figure 7-6 Kawabata bending tester

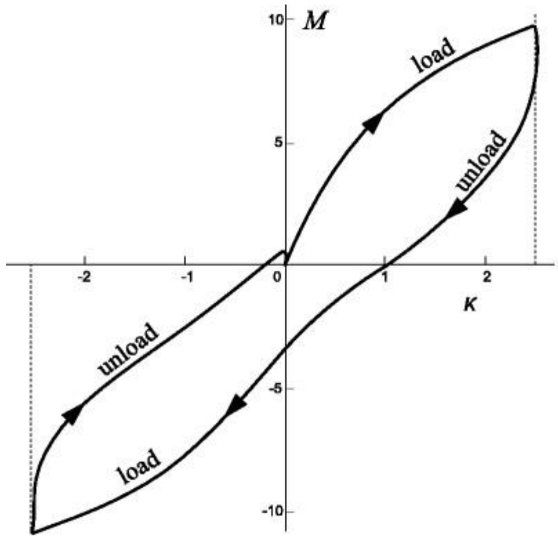

Figure 7-7 Moment versus curvature curve from the Kawabata bending system [127]

7.4 Bending model

This paper analyses the bending of a carbon fibre tow mainly based on it bending under its own weight and also the bending caused by the application of an external force; moment resulting in bending deformation or bending energy. Therefore the analysis of each of the methods maybe subdivided into:

- cantilever bending of carbon tow under its own weight;
- cantilever bending of carbon tow under an external force;
- three point bending under an external force.

7.4.1 Cantilever bending of carbon tow under its own weight

In deriving a relationship for beam bending, the problem can be approached from the fundamentals in the following way. A part of a bending beam can be depicted as shown in **Figure 7-8**.

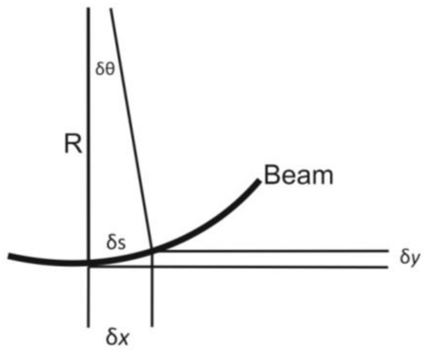

Figure 7-8 Part bending beam

Considering a small length of the bent carbon tow δs that subtends an angle $\delta\theta$ projecting a length of δx in the horizontal plane and a height of δy in the vertical plane, the following mathematical relationship can be derived.

For a small angle $\delta\theta$ the bending gradient of the tow, can be given as;

$$\frac{dy}{dx} = \tan \delta\theta = \delta\theta \quad ------------------------(1)$$

The curvature of the tow is defined as $\frac{d\theta}{ds} = \frac{1}{R}$ $---------------(2)$

Where R is the radius of curvature of the bending tow.

Therefore since $ds \simeq dx$

$$\frac{1}{R}=\frac{d\theta}{ds}=\frac{d\theta}{dx}=\frac{d}{dx}\left(\frac{dy}{dx}\right)=\frac{d^{2}y}{dx^{2}} \quad -------------- (3)$$

However according to the simple bending theory for bending beams,

$$\frac{E}{R}=\frac{M}{I} \quad -------------------- (4)$$

Where E is the Young's modulus, M is the bending moment and I is the second moment of area of the bending cross section of the tow about its neutral axis.

Therefore considering the equations (3) and (4) ;

$$EI\,\frac{d^{2}y}{dx^{2}}=M \quad ------------------- (5)$$

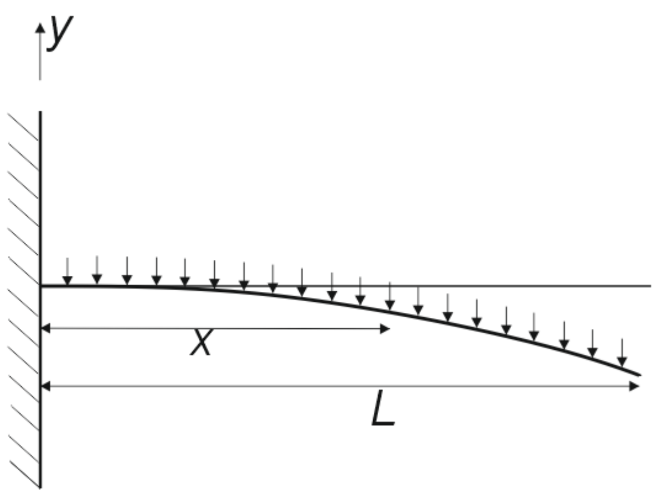

Figure 7-9 Cantilever bending under its own weight

Considering the cantilever bending situation shown in **Figure 7-9**,

M at a distance x from the point at which the tow is fixed and w is the force per unit length can be given as:

$$M = -\frac{w}{2}(L-x)^2 \quad \text{------------------------} (6)$$

The boundary conditions for this setup are:

Left end of the tow is rigidly fixed. When $x = 0$ $\quad \frac{dy}{dx} = 0$ and $y = 0$

Solving the 2nd order differential equation resulting from the equations (5) and (6), the deflection y at any point along the carbon tow can be give as:

$$y = \frac{1}{EI}\left[-\frac{w}{24}(L-x)^4 - \frac{wL^3}{6}x + \frac{wL^4}{24}\right] \quad \text{----------------} (7)$$

7.4.2 Cantilever bending of carbon tow under an external force

Figure 7-10 shows the setup in which the cantilevered and externally loaded carbon tow is held.

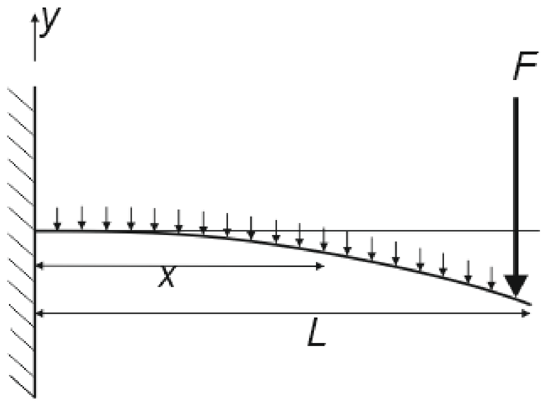

Figure 7-10 Cantilever bending under external force

For this setup the moment on the carbon tow at a distance x from the fixed point is given by;

$$M = -F(L-x) - \frac{w}{2}(L-x)^2 \quad -------------- \mathbf{(8)}$$

As in the previous case, the left end of the tow is rigidly fixed. When $x = 0$ $\frac{dy}{dx} = 0$ and $y = 0$

Therefore solving the equations (5) and (8) the deflection of the externally loaded cantilever beam can be given as;

$$y=\frac{1}{EI}\left[-\frac{w}{24}(L-x)^4-\frac{F}{6}(L-x)^3-\left(\frac{FL^2}{2}+\frac{wL^3}{6}\right)x+\left(\frac{wL^4}{24}+\frac{FL^3}{6}\right)\right] \text{----------}(9)$$

7.4.3 Three point bending under an external force

Figure 7-11 shows the setup for the three point bending test of the carbon tow.

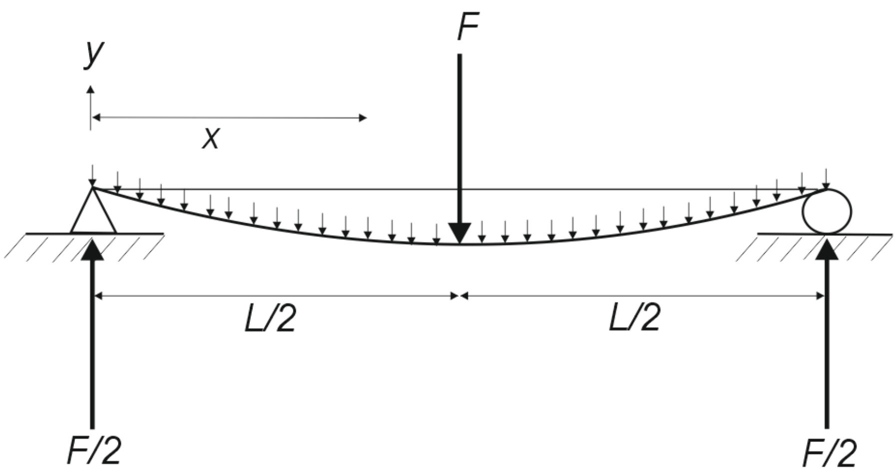

Figure 7-11 Three point bending under external force

For this setup the moment on the carbon tow at a distance x ($0<x<\frac{L}{2}$) from the left hand resting point is given by;

$$M=\frac{F}{2}x \quad \text{-----------------}(10)$$

For the boundary conditions: $x=\frac{L}{2}$, $\frac{dy}{dx}=0$ and when $x=0,\ y=0$

By solving the equation (5) and (10) together with the above boundary conditions, the relationship between x and y can be given as;

$$EI\frac{dy}{dx}=\frac{F}{2}\frac{x^2}{2}+C_1 \quad \text{------------------------} \quad (11)$$

Where, C_1 is the integration constant.

Considering the above boundary conditions and equation (11);

$$EI\frac{dy}{dx}=\frac{F}{4}x^2-\frac{FL^2}{16} \quad \text{------------------------} \quad (12)$$

Integrating again;

$$EIy=\frac{F}{4}\frac{x^3}{3}-\frac{FL^2}{16}x+C_2 \quad \text{----------------} \quad (13)$$

Where, C_2 is the integrating constant.

Since when $x=0, y=0$, from equation (13), y can be expressed as:

$$y=\frac{1}{EI}\left[\frac{F}{12}x^3-\frac{FL^2}{16}x\right] \quad \text{----------------------} \quad (14)$$

7.5 Results

Fabric bending rigidity is a major input parameter in FEA type software. Bending rigidity can be found using various methods such as the Shirley cantilever bending test, Kawabata bending test, and 2-point & 3-point bending test methods. The difference between the Shirley cantilever tester and the other test methods is that, in the Shirley tester the specimen is bent by its own weight and in the other test methods it is bent by applying an external force. These test methods were initially developed for garments. However, they were used here to see the effect of using the same methods on spread printed carbon tow. All tests were conducted on Toray T700 and MCF tow for which the results were compared.

Investigations into bending stiffness using the Shirley cantilever test method have shown that there was a marginal increase in stiffness of the spread printed tow compared to that of the raw tow. Also there was difference in bending stiffness according to the direction of bending and the printed surface, which can be seen in Figure 7-12. From the figure it can be clearly seen that there was consistency in results between the samples in repeat tests.

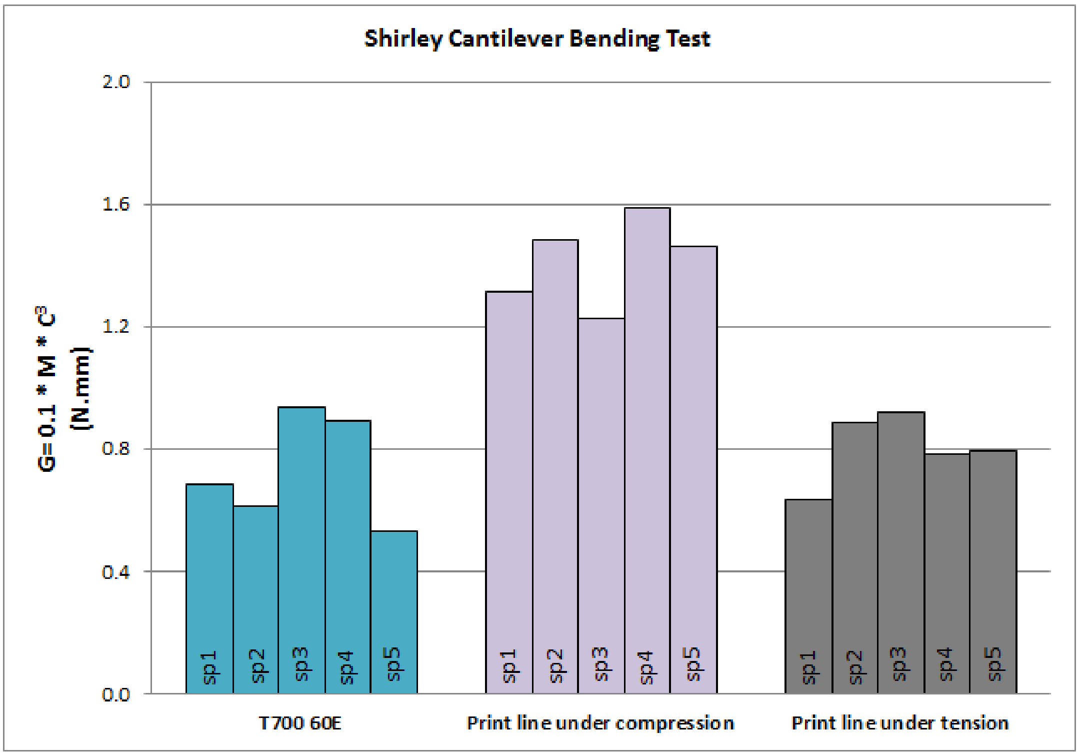

Figure 7-12 Bending rigidity of raw and printed carbon tow using the Shirley tester

The tow was placed on two anvils and force was applied to the centre for the 3 point bending test. From the force versus deflection shown in **Figure 7-13** it can be seen that there was variation between the repeat tests in the case of raw tow. In the case of printed tow under compression the four specimens produced similar results and one was higher comparatively as can be seen in **Figure 7-14**. When the print line was under tension there was a similar trend between the results, as shown in **Figure 7-15**.

Three point bending tests have shown that there was a marginal increase in bending stiffness when the tow was bent in the direction opposite to the printed surface and the printed side under tension. When the tow was bending in the same direction as the printed surface and the print side was under compression, it was found that the bending stiffness was lower than for raw tow this can be seen in **Figure 7-22**.

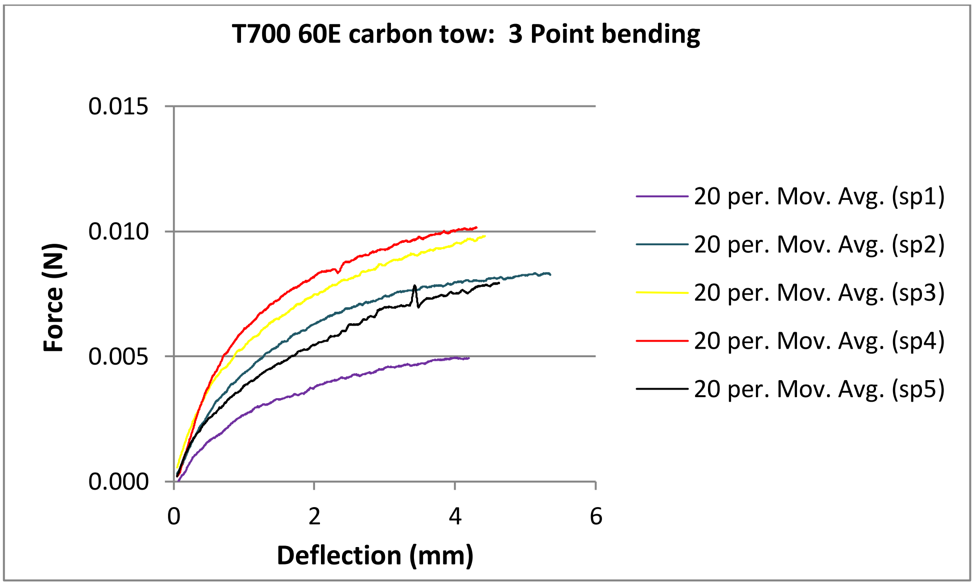

Figure 7-13 Toray 60E carbon tow force versus deflection from the 3 point bending method

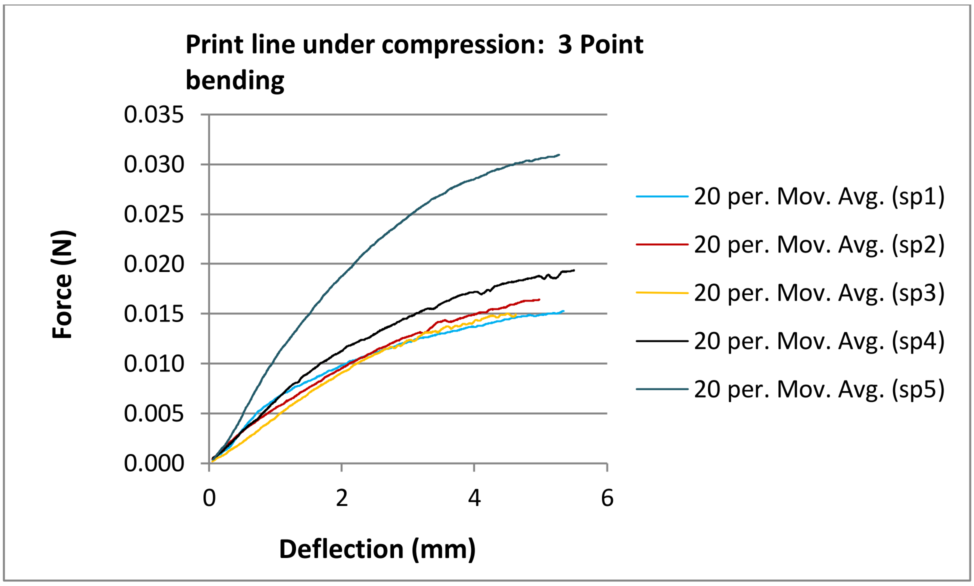

Figure 7-14 Printed carbon tow under compression force versus deflection from the 3 point bending method

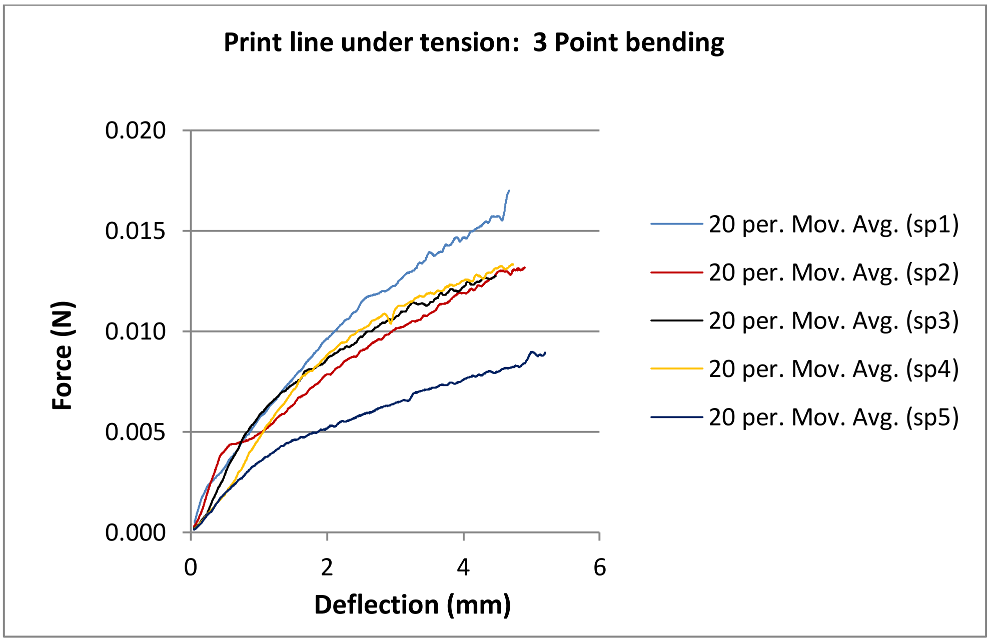

Figure 7-15 Printed carbon tow under tension force versus deflection from the 3 point bending method

Figure 7-16 shows that in the case of raw tow there was marginal variation between the repeat tests in the 2 point bending test method, similar to that in the case of the 3 point test method. When the print line is under compression there was a similar trend between the samples for four tests and one was higher compared to the others, as seen in **Figure** 7-17. Also in the case of the print line being under tension, there was similarity between the tests as can be seen in **Figure 7-18**.

In the case of the two point method, the bending stiffness was found to be marginally higher for raw tow compared to that of the printed tow as maybe seen in **Figure 7-22**.

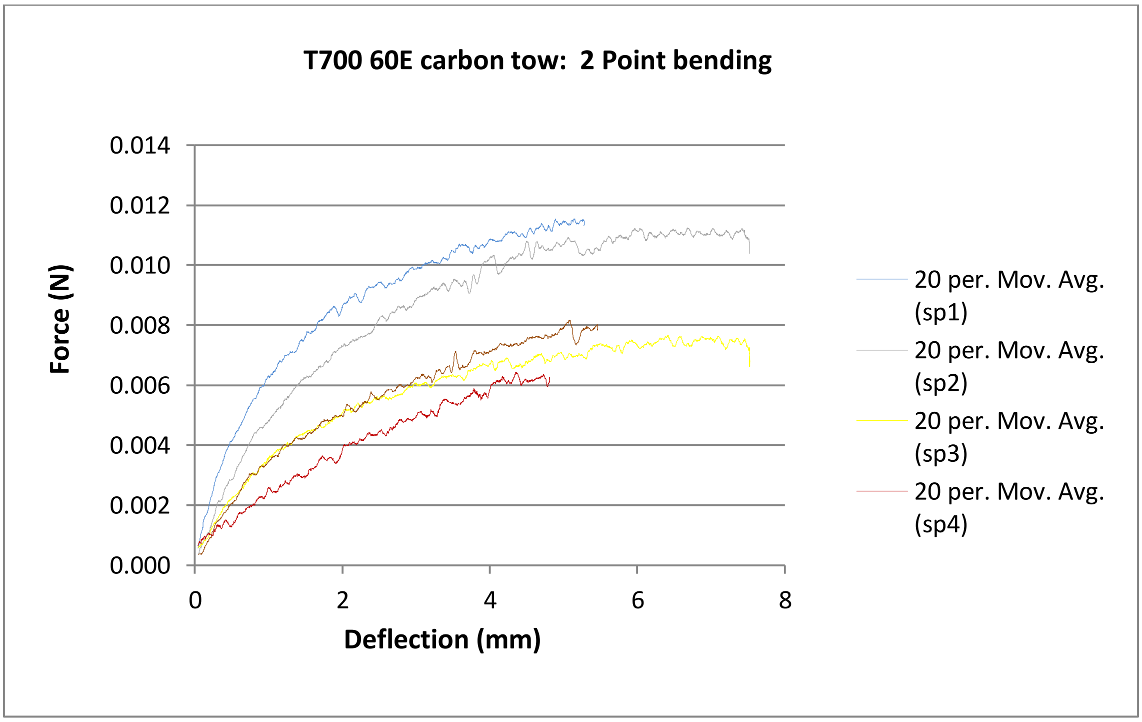

Figure 7-16 Toray 60E carbon tow force versus deflection from the 2 point bending method

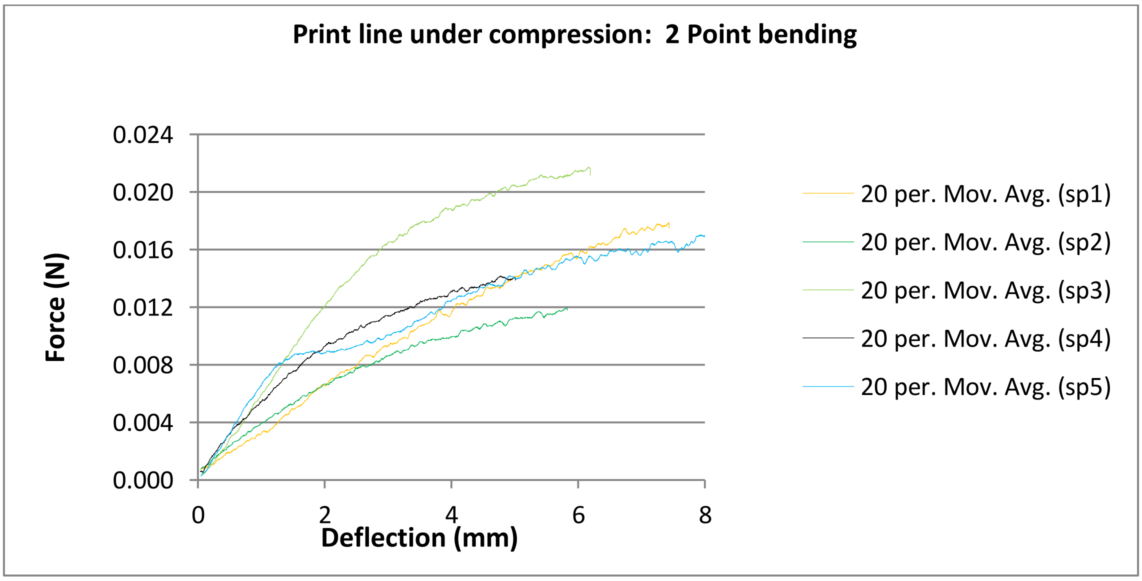

Figure 7-17 Printed carbon tow under compression force versus deflection from the 2 point bending method

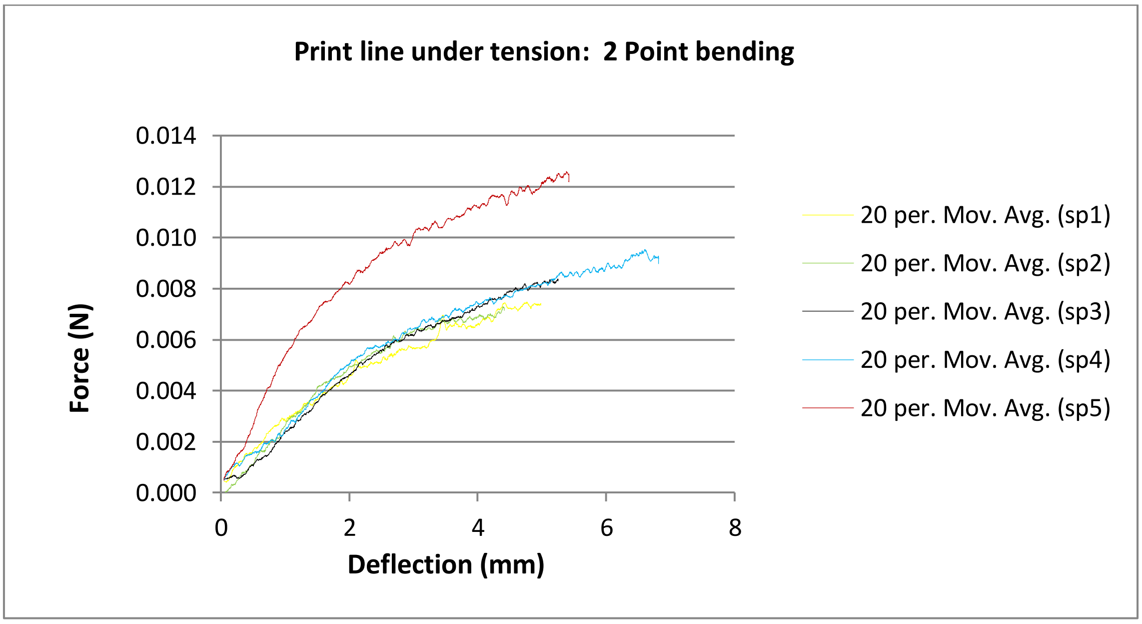

Figure 7-18 Printed carbon tow under tension force versus deflection from the 2 point bending method

There was a similar trend in the moment curvature curve in the case of raw carbon tow as seen in **Figure 7-19**, but in the case of printed tow under compression as seen in **Figure 7-20** and under tension as shown in **Figure 7-21**, there was a noticeable difference between the repeat tests. This was due to the short distance of 1cm between the chucks and also in a 1 cm sample there is only one print line, hence this significantly influences the bending properties. This can also be due to the tow being held at one end and force being applied at the other end, resulting in a low bending stiffness value, due to low inter fibre friction.

Even though the Kawabata bending tester was originally developed for garments, this was also useful for giving an indication of the bending stiffness of the carbon tow. The results from the Kawabata test have shown that there was an increase in bending stiffness of the printed tow compared to that of raw tow. Also there was a considerable difference between the direction of bending of the printed tow according to the print surface and the non-print surface as may be seen in **Figure 7-22**.

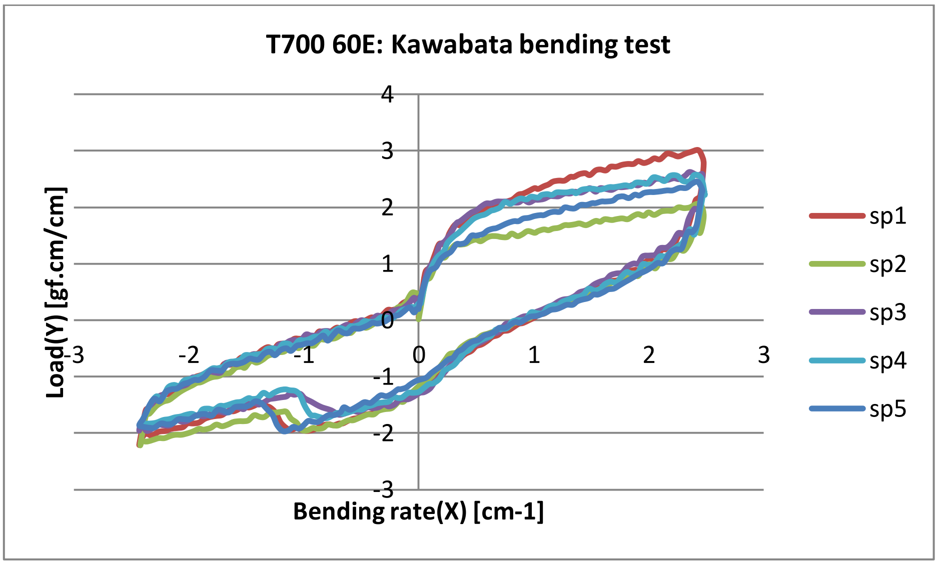

Figure 7-19 Bending moment/curvature curve for Toray 60E carbon tow

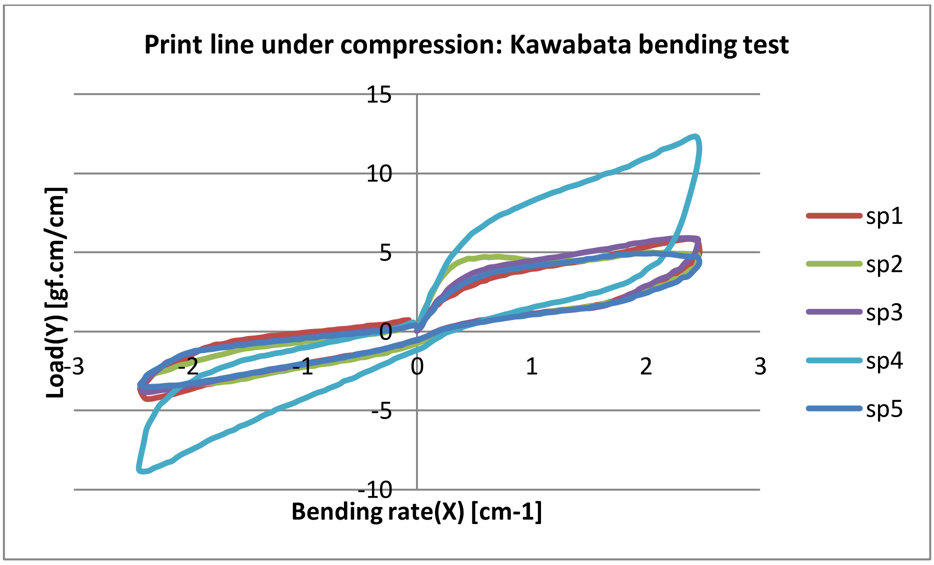

Figure 7-20 Bending moment/curvature curve for printed carbon tow under compression

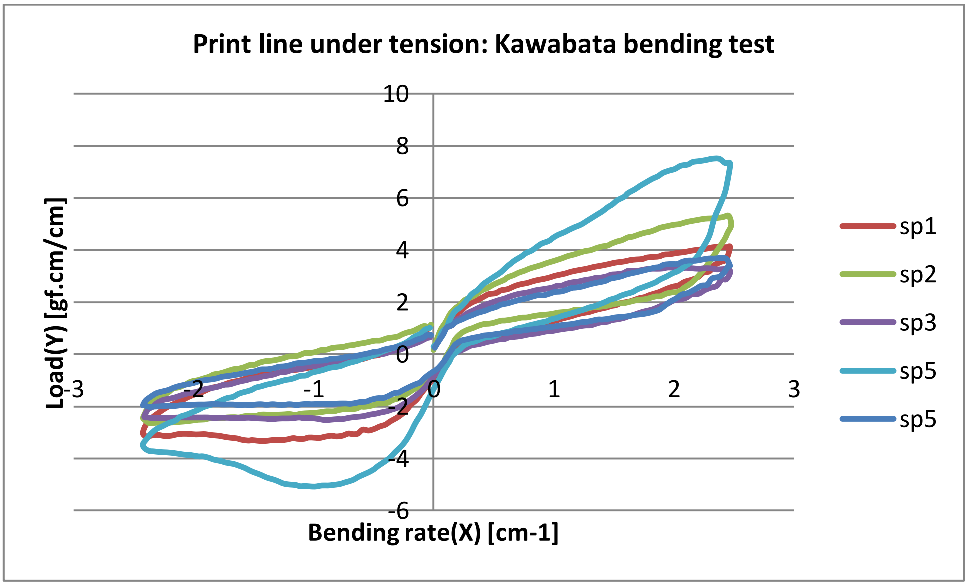

Figure 7-21 Bending moment/curvature curve for printed carbon tow under tension

From **Figure 7-22** it can be seen that there was a good correlation between the test results of 2 point & 3 point, Kawabata and cantilever bending test methods even though the principles for bending are different in all cases (the cantilever bends under its own weight, whilst the 2 point & 3 point and Kawabata specimens bend by applying a force or a bending moment).

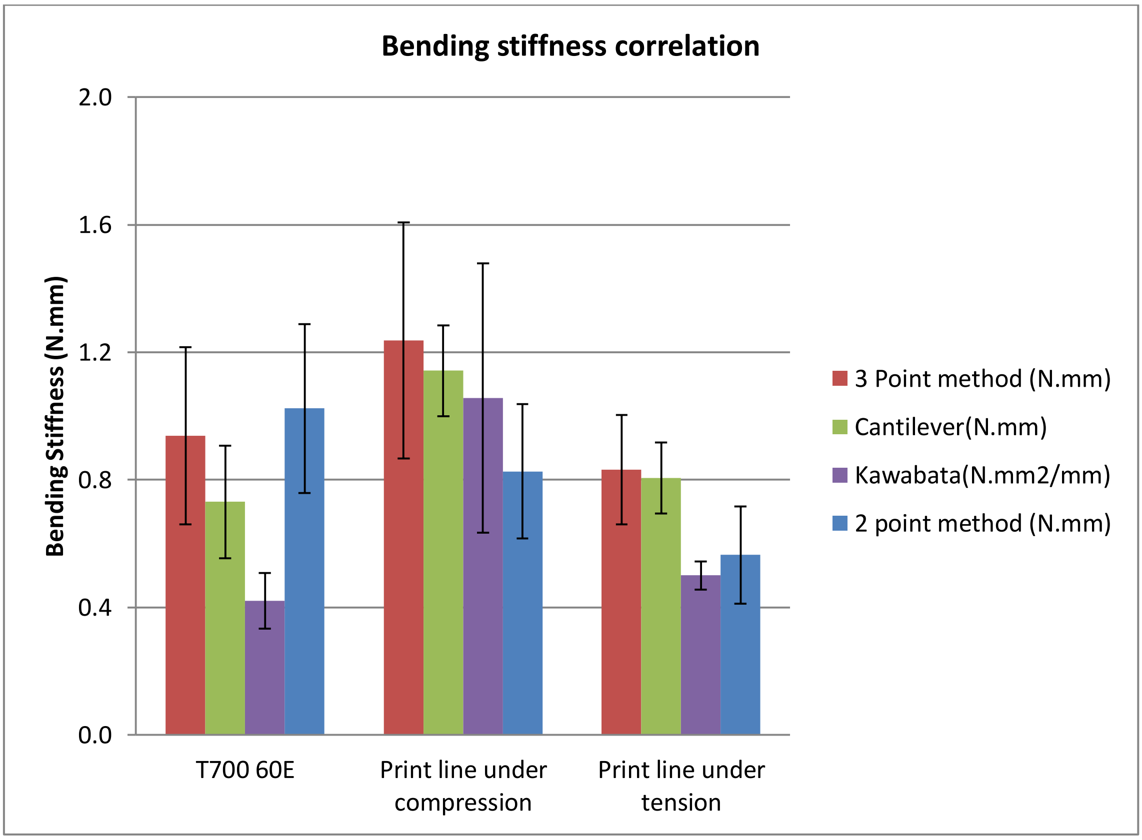

Figure 7-22 Bending stiffness correlation of 3 point, Shirley cantilever, Kawabata and 2 point cantilever bending test methods

7.6 Conclusion

The research into different bending stiffness the methods has shown that there was a similarity between the bending stiffness found using the cantilever, 2 point & 3 point, and Kawabata bend test methods. Even though the principles of both approaches are different, as in the case of the cantilever test, the tow bends under its own weight and in the case of two point, three point and Kawabata bending test methods the weight of the tow was not an important factor as the tow bends under external force. In the case of Kawabata testing there is only a 10mm gap between the two chucks and in 10mm there is only room for one print line - this affects the bending stiffness properties significantly.

A analysis of the results of the various bending stiffness test methods has shown that for shorter lengths, the stiffness value varies considerably, and this can be seen from the Kawabata test results. For longer bending lengths there was more consistency between the results of 2 point & 3 point, and Cantilever bending test methods. The bending stiffness of the carbon fibre tow depends on the bending direction and on the interaction between fibres and the frictional resistance.

References

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Chapter 8. Conclusion and future study

8.1 Summary of findings and accomplishments

This study was mainly focused on the design and development of multifunctional carbon fibre flat tape. Various laboratory scale machines for the creation of MCF flat tape were developed. Finally a prototype machine to manufacture four flat metallised carbon tows was developed. The materials made using different methods were characterised using mechanical tests and the results were validated using ANSYS simulation software.

8.1.1 Metallisation process development

Three different processes were developed to produce multifunctional carbon tow. The first process was designed to co-mingle carbon/cobalt wires by passing them through a size bath to bind them together. The main disadvantage of this technique was that the adhesion between the cobalt wire and carbon fibre was found to be weak resulting in separation of the cobalt wire from the co-mingled tow during handling. Also the addition of epoxy size on to carbon tow increased its bending stiffness. In the second process, nickel powder was applied on to the surface of the carbon tow. Powder was glued to the carbon tow using epoxy size, but the problem with this technique was that the poor cohesion that existed between the nickel powder and the carbon tow. Finally in the third process, nickel powder was mixed with water based epoxy and printed as transverse patterns of lines, intermittently on the surface of the carbon tow. This process was found to be commercially viable compared to the previous two processes.

Therefore in conclusion the investigation carried out showed that the production of MCF through printing of metallic lines in a transverse direction on the carbon tow had the best mechanical performance. In this way the flexibility of the carbon tow was maintained whilst achieving the required magnetic performance.

8.1.2 MCF material development by printing of metallic grating and FE analysis

As presented in chapter 4, a mechanical test of the MCF was carried out and the FE model for the same was also generated. When changing the position of single print lines under the cylindrical magnet it was observed that the change in the magnetic force experienced by the MCF tow due to transverse displacement of half its width is negligible. This behaviour was validated using the finite element model. Further pull force tests were conducted for multiple print lines under an array of magnets by shifting the MCF tow horizontally. The difference in pull force due to this shifting was found to be negligible. The model of horizontal shifting of MCF tow and the experimental results showned agreement. A further test was performed by shifting the magnets vertically from the tow, where both the experiment and the model had shown good correlation. The bending properties of the MCF tow under the influence of the magnetic field were also studied. The deflection due to the magnetic field in the experiment and model had similar results.

In conclusion, tests have shown that printing a pattern of transverse lines is a good way to create the MCF tow, as the tow was designed to bend in a transverse direction on the mould surface during the preforming process. The use of MCF tow, in the already established process of DCFP has the advantage of improving the efficiency of the process by using magnetic tooling, and also improves its functionality.

8.1.3 Characterisation of the MCF tow

The multifunctional carbon tow developed using the printing process was characterised by various mechanical tests. The ferromagnetic material content on the MCF was varied by different methods such as changing the powder percentage in the print line, increasing the distance between the print line and by changing the width of each print line. Magnetic pull tests and bending stiffness tests were conducted on all the variations. It was observed from the bending stiffness test by changing the size concentration that there was considerable increase in stiffness from 0.5% epoxy size to 1% epoxy size after that the stiffness values was very similar for 1.5% and 2% this was due to the fibres binding together after 1% and before that there is slippage between the fibres.

The effect of metallic powder quantity on the magnetic pull force and bending stiffness was studied and the results showed that as the powder quantity increased the magnetic pull force increased. However, in the case of bending stiffness, the results were found to be similar. As the metallic line spacing increases, the magnetic attraction decreased. Also it was observed that the bending stiffness had also decreased as the line spacing increased. Magnetic attraction increased as the width of each print line increased but the bending stiffness showed negligible differences.

It can be concluded that the maximum mould thickness using the current MCF tow is 7mm, however this can be increased further by increasing the strength of the magnetic field. From this study it can be summarised that the MCF tape can be systematically engineered based on the shape of the mould surface and magnetic field.

8.1.4 MCF material development by co-mingling and the FEA model

Epoxy size is a major component of the MCF tow as it is directly related to the bonding strength of cobalt wire on the surface of the carbon tow. There was an increase in the bending rigidity of the co-mingled tow with increase in size concentration. This increase creates problem in bending the tow along the curvature of the mould surface during the deposition process. A FE model of the magnetic force experienced by the cobalt wire was also created.

In summary the process to co-mingle carbon fibre with cobalt wire was developed and the resultant material was characterised by mechanical tests. The purpose of co-mingling the cobalt wire with carbon was that once the chopped tow are placed on the complex shapes of the mould surface, the magnetic field holds them until the resin infusion. For the co-mingled tow developed for this study the maximum mould thickness is 7mm, however it is possible to increase the thickness of the mould further by increasing the strength of the magnets.

8.1.5 Bending stiffness study and mathematical model

Bending rigidity is a major input parameter in the simulation software. Bending stiffness of the single MCF was measured using different principles i.e. by bending its own weight and by application of external forces. The results from the cantilever and three point bend tests showed good correlation. The stiffness from the three point bend test was used in the mathematical model to validate the experiment of bending the MCF tow under the influence of a series of magnets. Further bending stiffness study was conducted by Kawabata and 2 point test methods. When the 2 point bend test, 3 point bend test, cantilever bend test and Kawabata test methods were compared. It was found that there results of all the test methods were comparable, except for the raw tow bending stiffness from the Kawabata method. This is due to the inter fibre slippage due to the short distance between the clamps.

It can be summarised from this study that to identify the bending stiffness of the carbon tow, either the 2 point, 3 point bend test method or cantilever method can be used as the bending rigidity value obtained using those principles were identical.

8.2 Future study

The following paragraphs present future work that can be carried out in order to investigate alternative applications of the multifunctional MCF tow.

8.2.1 Icing

Preliminary study had shown that by incorporating metal on the carbon tow, there was an increase in the temperature produced by the MCF tow when current passed through it. It is envisaged that further studies need to be conducted in order to characterise the effect of metal on carbon tow for heating applications. A thermal image of carbon tow Toray T700 was obtained by passing Voltage -10V, Current -1A and room temperature-27^{0}C as illustrated in **Figure 8-1** and it provides initial observations on this topic. The same test was repeated on cobalt /carbon commingled tow and this can be seen in **Figure 8-2**. There was an increase in heating of the commingled tow. Further tests need to be conducted by varying the number of cobalt wire to study this effect. Also the effect of infused composites made using the commingled tow heating need thorough investigation.

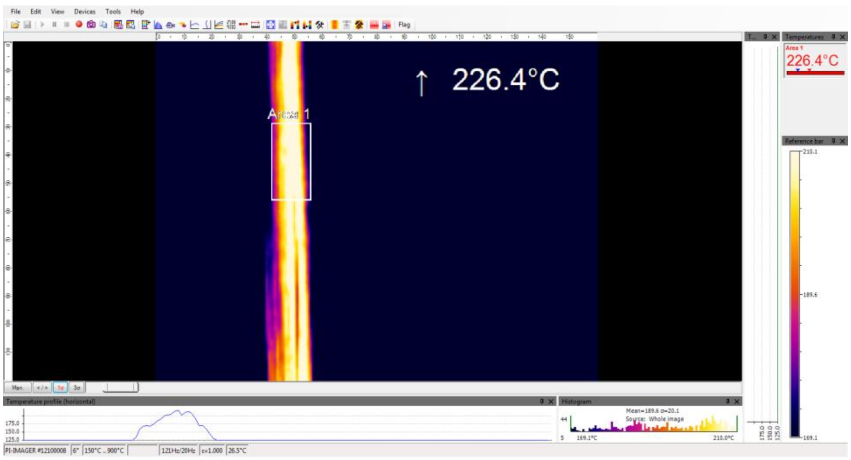

Figure 8-1 Toray T700 heating

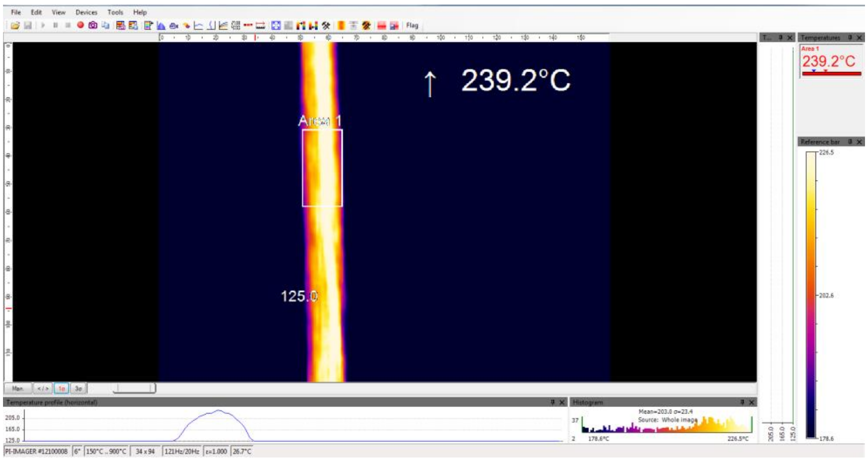

Figure 8-2 Carbon/cobalt commingled tow heating

8.2.2 EMI shielding

Even though nickel coated carbon fibre produced using electro deposition are currently available for EMI shielding, the effects of carbon fibre co-mingled with cobalt wire need to be explored.

8.2.3 Spread tow panel

To investigate the application in spread tow panels, composite panels need to be produced using the spread tow made using the prototype machine developed as a part of this project. Tests need to be conducted to identify its mechanical properties compared to those of raw carbon tow. The **Figure 8-3** shows the image of spread tow made using the MCF machine.

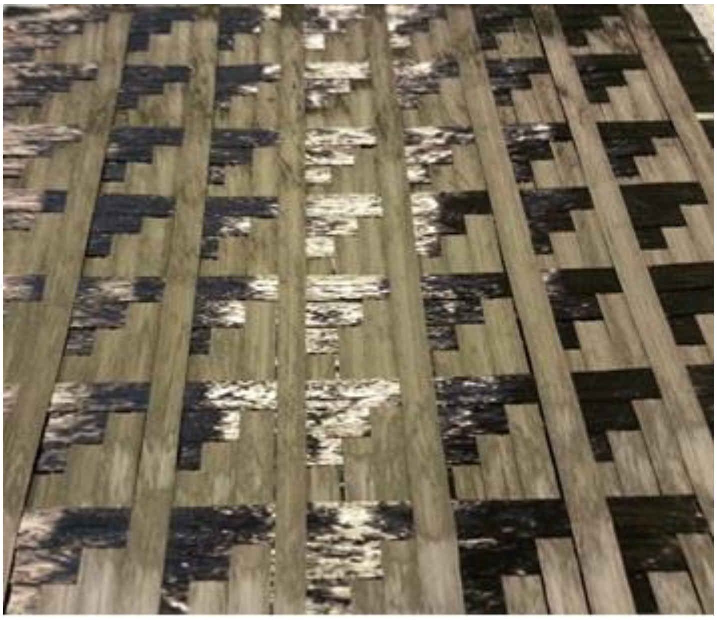

Figure 8-3 Tow placement using spread tow

8.2.4 Thermoplastic powder coating

The system developed for nickel powder deposition can be used for thermoplastic powder coating. The process would involve the passing of the carbon tow through a size bath and spreading rollers followed by application of thermoplastic power on to the surface of the carbon tow or by passing the carbon tow though a container filled with powder and by removing the excess powder when the tow comes out of the container. The resulting thermoplastic powder applied can be cured thereafter using infrared heating followed by flat winding on to a bobbin.

8.2.5 Coating graphene nano platelets

The current process of incorporating GNP into bulk resin had been found to be ineffective and expensive. The prototype machine developed can be used for coating spread carbon tow with GNP.

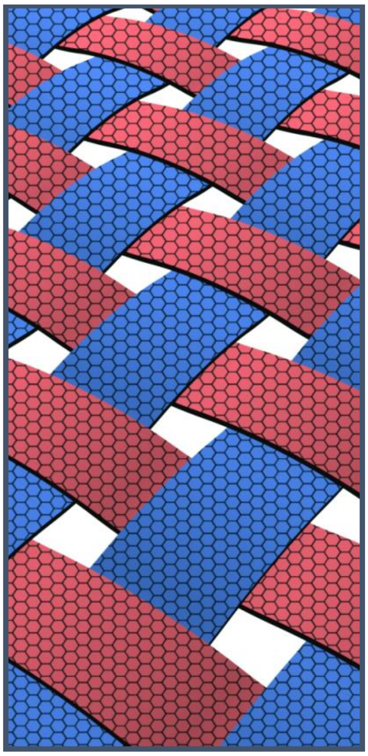

Figure 8-4 GNP coated carbon spread tow

This material has several applications such as damage resistance, real time structural health monitoring, etc. **Figure 8-4** shows the image of GNP coated on the surface of the spread carbon tow.

8.3 Research Publications resulting from the study

The chapters 4 to 7 comprise the research papers written with a view to submitting them for reputed journals. The following is a list of them giving the current state of them in the process of submission.

- Dodworth A[a], Potluri P[b], Koncherry V[b], Rashed K[b], Sharif T[b]. *"Magnetized carbon preforming for automotive composites"*. International Conference on Manufacturing of Advanced Composites, Belfast 2011. ([a] Bentley Motors Ltd, [b] The University of Manchester)
- Koncherry V, Potluri P, Fernando A. *"Multi-functional carbon fibre flat tape for composites"* 19th International Conference on Composite Materials, Canada, 2013
- Koncherry V, Potluri P, Fernando A. *"Functionalization of carbon fibre tows through metallisation for automotive composites"* Composites Part A: Applied Science and Manufacturing, (in submission)
- Koncherry V, Potluri P, Fernando A. *"Effect of size and ferromagnetic material on metallised carbon fibre preform for composites"* Journal of Composite Materials, (in submission)
- Koncherry V, Potluri P, Fernando A. *"Process development and characterisation of carbon fibre and cobalt wire commingled tow for composites"* Journal of Composite Materials, (in submission)
- Koncherry V, Potluri P, Fernando A. *"Measurement of carbon tow bending stiffness using different test methods"* Textile Research Journal, (in submission)

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