MULTI-FUNCTIONAL CARBON FIBER FLAT TAPE FOR COMPOSITES

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1 Introduction
In the current economics of the world, the cost of manufacturing carbon fiber based composites is one of the main concerns of the high volume producers, in this industry. Addressing this concern requires both material and process improvements, namely; the use of low cost carbon fiber as well as an efficient and high throughput production process. Directed carbon fiber performing (DCFP) is one such production process in which chopped carbon tow is sprayed on to a mold surface, which is then held on to the mold surface using a positive airflow. The research into an advanced version of this process, i.e. the production of carbon composite preforms using functionalized carbon tow, with the aid of magnetic tooling, in the presence of a magnetic field was carried out by the composites research team of the University of Manchester in partnership with Bentley Motors Ltd and Nottingham University[1, 2].

Currently, the micro scale of the carbon fibers practically prevents the carbon being handled in the form of fibers. Therefore they need to be in the form of a bundle of fibers or in the shape of a tow. Specifically in the research carried out in the area of DCFP, tows having a width 6-7 mm and a linear density of 800 Tex, consisting of 12000 fibers is used.

The concept of depositing carbon tow on to a mold surface, with the help of the DCFP process has been identified as one of the most economical methods by which carbon fiber composites can be manufactured [3, 4]. The process consists of chopping carbon tow and blowing the chopped pieces on to a mold surface to create the necessary molded components. The binder which helps to solidify this shape can be introduced either during or after the placement of the fibers.

According to the conventional DFP (Directed Fibre Preforming) method (Figure 1)[5], on which the DCFP process is based, the mold surface used needs to be porous so as to facilitate the diffusion of positive air flow that is used to hold the chopped fibers in place [6-8].

Figure 1: The conventional DFP [5]: (a) Fiber deposition, chopped fiber 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) Demolding, preform removed from the lower screen

This feature of the mold in turn results in an inherent problem during molding due to the escape of some
of the short fibers together with the air extracted. As reported by Harper et al [3], the low density carbon fibers tend to get disrupted, particularly on vertical surfaces of the mold tool, due to the suction air streams. The resulting need for constant cleaning of the mold surface causes the DCFP to have downtimes in the production which subsequently affects the efficiency of the process.

Therefore the main aim of the current research paper is to present a solution to the above issues, put forward by the team of researchers who specializes in the functionalization of carbon tow for composite manufacturing at the University of Manchester. As recognized by them, it is possible to address the issues through the functionalization of the carbon tow by replacing the positive air flow tooling used during the molding process. This is carried out by converting the carbon tow in to a material that can be magnetized and therefore replacing the air tooling used with magnetic tooling, it is possible to work with non-porous mold tools. Even though in the previous applications, the use of DCFP was limited to non-metallized fibers, the relative advantages of using MCF (Metalized Carbon Fibers), makes it a prime candidate for the DCFP process.

Through the experiments conducted, the DCFP process that uses MCF was found to address the issues of positive air based DCFP, due to the electromagnetic force it uses to hold the chopped tows on to the mold surface (Figure 2). The main advantage of using MCF is the relative ease with which carbon tow can be made to cling to the mold surface. By placing the mold 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 mold surface itself. This allows the resin infusion to be carried out for consolidating the component being molded, without the problem of fiber escape.

The success of the MCF approach to the DCFP process is further proved by the result of the demonstration carried out, in order to produce a magnatisable molded spare wheel well of a motor vehicle, as shown in the Figure 3.

![Figure 2 Chopped fibre applied to mould and held by electromagnetic force.](image)

![Figure 3 Spare wheel well made using metallized carbon tow (Bentley Motors Ltd.).](image)

### 2 Effects of process variables on the metallized carbon tow

To create metalized carbon fiber tows, a manufacturing process capable of producing sized and metalized tows was developed. 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 mold. 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 epoxy 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 stiffness’s in the tow requires extensive experimentation.

The weight increase of the metalized 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 metalized carbon tow for an electromagnetic field used for the molding 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 localized pattern. Independent research has proved that uniform coating of carbon fibers 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 [9]. To reduce the increase in stiffness, it is possible to magnetize 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 length wise metallic powder lines will cause higher bending stiffness’s 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 since 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 [10];

\[ F = A \frac{[B(x)]^2}{2 \mu_0 \mu_r} \]  

(1)

Where

- \( F \) = magnetic pull force
- \( A \) = area of the disc magnet
- \( B \) = flux density on the MCF tow
- \( \mu_0 \) = magnetic permeability of free space
- \( \mu_r \) = relative magnetic permeability

The flux density of the disc magnet at a distance ‘x’ from the magnet can be given by [11];

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

(2)

Where;

- \( B_r \) = 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)

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

(3)

The equation (3) shows that the relationship between the air gap height, from the magnet to the MCF tow, and the pull force.

3 Experimental Methodology

Initially the research conducted for metallization of carbon fiber tow investigated three different approaches to their production. These approaches are namely; co-mingling with ferromagnetic wires, coating carbon fiber tow with ferromagnetic powder and Line printing of metallic powder. Out of these three approaches, the introduction of a ferromagnetic material through printing has proved to be the most
suitable form of production for the MCF tow. In this metallization technique, a sized carbon tape that is spread to the required width is printed with lines of epoxy nickel powder paste intermittently (Figure 4 and Figure 5). The resulting metalized tape is heat cured using a process of cylindrical contact heating which is subsequently cooled in to the final metalized tape before flat winding on to bobbins. As in the case of DCFP, the current research work carried out to produce and characterize the MCF tow, 12K T700 Toray carbon tape with a linear density of 800 Tex and fiber diameter of 7 micron was used in the experiments. Ferromagnetic material used to metalize the samples was nickel powder (Type 123). The epoxy size used to bond the ferromagnetic material on to the carbon tape was a water-based epoxy (EPI-REZ™ from Hexion).

In order to observe the effect of metallic powder concentrations, the first step was to create varying mixtures of Nickel powder and epoxy. The viscosity of the original epoxy was 18000 cP. During the production of 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 the steps of 20%, 30%, 40%, 50% and 60% of the weight of epoxy. This mixture was applied on to the carbon fiber tow in the form of transverse lines in a uniform pattern. Thereafter experiments were conducted to measure the magnetic attraction using an array of magnets with a combined pull force of 14kg. The magnetic attraction force was recorded while reducing the distance between the magnets and the metalized 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.

For all these tests to determine the effect of metallic powder, the tow sizing was controlled at 1% to prevent filamentation, and the tensile tester was run at the speed of 5mm/min. A 25N load cell was used in the tensile tester during these tests (Figure 6).
Analyzing 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 a curvature of a mold used to create a preform, a 3 point bending test was carried out according to the test standard BS ISO 5628:2012(Figure 7 (a))

![Figure 7 (a) Three point bending test and (b) MCF tow bending under the influence of the permanent magnetic field](image1)

**4 Results and Discussion**

Due to the nature of magnetic fields, during the preforming process, the quantity of metallic content in the metalized tape is a measure of electrical energy used. Therefore, higher the mass of metallic aggregate in the tape, less electricity will be consumed by the electromagnetic tooling to create the preform shape.

To realize this advantage, magneto-mechanical characterization of the metalized tape is essential in order to determine the optimum metallic content for the tape. Further, the bending stiffness of the MCF tape was also investigated to determine the bending energy requirement of the pieces of chopped tape in the preform during the preforming process. Tests were carried out to observe the effect of varying the linear density of the ferromagnetic material, the sizing content and the geometry of the lines deposited in the sense of its thickness and the orientation/pattern of the lines. Printing with metallic grating demonstrated consistency in the magnetic pull force as the powder percentage varied.

### 4.1. Effect of the metallic powder quantity on the magnetic pull force

Previous experiments conducted to observe the suitability of sprinkling for incorporating the metallic 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 the Figure 8.

![Figure 8 Variation in magnetic pull force due to the air gap and ferromagnetic powder](image2)
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.

4.2. 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 (Figure 9). Therefore the behavior 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 better distribution of the metallic lines are provided. This will reduce the localized concentrations of weights, provide a better distribution of metallic lines in the standard chopped tow size of 2.5-7.5 cm [12, 13] 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 or thicker print lines promote air gaps in the molds 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.

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.

4.3. Effect of the metallic line width on the magnetic attraction

Same as in the above cases, increasing the metallic line width has the effect of increasing the quantity of metallic powder incorporated to the tow. Therefore no change was observed (Figure 10) in the quadratic relationship between the air gap and the pull force.

![Figure 10 Magnetic pull force for varying metallic line widths.](image1)

It can be understood that as long as the metallic line width is maintained fine, the capability of the MCF tow to assume any curvature of the mold 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 epoxy size was not mechanically removed from the tow, 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 (Figure 5) 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 on to the tow. Since this is an undesirable outcome, during printing metallic lines on the tow, every precaution was taken to ensure that the exact predetermined paste quantity was printed.
4.4. Three point bending test

<table>
<thead>
<tr>
<th>Carbon Tow</th>
<th>Bending Stiffness (N.mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toray T700 60E</td>
<td>1.15</td>
</tr>
<tr>
<td>Print Lines on Top</td>
<td>4.04</td>
</tr>
<tr>
<td>Print Lines on Bottom</td>
<td>3.81</td>
</tr>
</tbody>
</table>

Table 1 Bending rigidity calculation for MCF tow according to the BS ISO 5628:2012

The determination of the Young’s modulus for modeling 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;

\[
S_b = \left( \frac{F}{f} \right) \left( \frac{l^3}{3b} \right)
\]  

(4)

Where

\( F \) = force,  
\( f \) = linear deflection,  
\( l \) = bending length,  
\( b \) = specimen width

As the Table 1 shows, the original bending rigidity of the carbon tow is higher due to the metallization process. Also according to Table 1, the bending direction, whether in 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 derived from the results of Table 1 was used for the MCF tow material definition in the Ansys analysis.

4.5. Bending deflection under a magnetic field

The mathematical modeling of MCF tow bending was carried out to observe its capacity to assume the curvature of a mold surface.

The validation of the model (Ansys simulated deflection of 2.22mm and the experimental value of 2.17mm) shows that the Ansys finite element model created for MCF tow bending 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 (Fig. 7. (b)).

5 Conclusion

Epoxy waterborne resin size is a component of the carbon tow which binds the carbon fibers together. In engineering the metalized tow, first the size quantity is decided to obtain the minimum stiffness for conforming to the smallest mold 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. The epoxy size quantity in the tow used for the present research is 0.3%.

The tests to measure the magnetic pull force between the MCF tow and the permanent magnet describes a relationship similar to that defined in the equation 3. All the experiments to measure the magnetic pull force shows that each method of metallic powder is introduction increases the magnetic pull force on the carbon tow. However this has to be carried out so that the low bending stiffness of the MCF tow is preserved. Metallic lines are introduced at various line separation and line width values. Again having the minimum printable line width is advantageous. Also it was seen that if the lines were printed too near, they tend to merge together, increasing the stiffness of the tow. Therefore the tests conducted shows that in this particular case a metallic line width of 1mm, a line separation of 10mm, 0.3% size quantity and 40% quantity of metallic powder is most appropriate.

The purpose of applying metallic lines is that once the chopped tow pieces are placed on to the mold to a specific thickness, the magnetic field of the mold will be capable of compacting the chopped tows against the mold surface. From the Figure 8, Figure 9 and Figure 10, it can be deduced that for the present case a maximum of 10 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.
Analysis of the bending tests carried out on the MCF tow under the magnetic force exerted by the magnet array showed that the magnetic field is capable of causing the tow to bend and assume smaller radii. Also the bending experienced under sudden impulsive bending was observed as reversible as well. However further studies to investigate the pile size of tows that the mold magnetic field can hold and the bending stiffness and the energy requirement would be of great importance to the use of this technology for component preforming.

Acknowledgements
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References