Carding of Recycled Carbon Fibres

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In recent years the demand for carbon fibre has increased, mainly due to its wide variety of potential industrial applications, including the use of carbon fibre-reinforced materials in the aerospace, automotive, and defence industries. Carbon fibre has a number of advantageous properties that make it highly versatile. For example, it has a very high tensile strength and low density. The current high demand, which is predicted to rise in the future, means that the amount of waste carbon fibre is increasing. ELG Carbon Fibre (ELGCF) recover carbon fibre waste from the aerospace industry and turn it into non-woven materials that can be used in other industries, such as the automotive industry.

ELGCF's processing of waste carbon fibre involves multiple stages. We focus on the carding stage, where the carbon fibres pass through a carding machine, which turns the disordered fibres entering the machine into a homogeneous oriented web of aligned fibres that can then be processed. Carding machines are widely used in the textile industry, and consist of a set of toothed cylinders of different sizes, moving at different velocities. The roll of the teeth is to both align the fibres and to transfer fibres from one cylinder to another, which is also aided by the relative velocities of the cylinders. The fibres are fed into the carding machine by a rotating feed sheet and a number of rotating cylinders before they are passed onto the main cylinder. They travel around this main cylinder, which has several pairs of cylinders along its edge. The two cylinders in each pair are called the worker and the stripper. After the fibres have travelled along the main cylinder, passing through each worker/stripper pair, they are then taken off by more rollers. Our aim is to use a continuum approach to build a model for the carbon fibres moving through the carding machine, so that we can examine what properties are desirable in order that the carding machine efficiently produces a web of aligned fibres.

The Model

We consider the region between between two cylinders, shown in figure 1. We model the behaviour of fibres by adapting a continuum model for carding in the textile industry to derive a two-dimensional model in a thin layer, making use of the fact that the distance between cylinders is much less than the radii of the cylinders. The model consists of equations for conservation of mass, conservation of momentum, a kinematic condition, and a constitutive law for the *order parameter*. The main properties that we want to examine are the evolution of the density of carbon fibres, and the order parameter of these fibres. The order parameter is a measure of how aligned the carbon fibres are, being equal to 1 if the fibres are fully aligned, and 0 if they are randomly oriented.

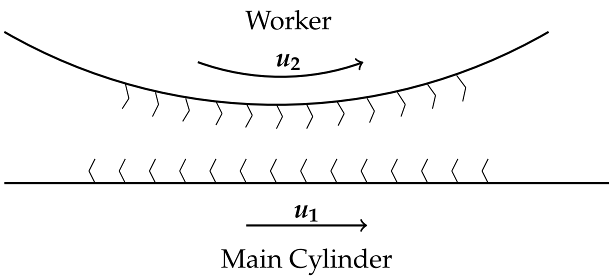

Figure 1 – Schematic of the region between the worker, moving at velocity u_2, and the main cylinder, moving at velocity u_1. The hooks along the surface of the cylinders, and their relative orientation, are also shown.

Results

We solve our model explicitly and plot the distribution of the density of the fibres and their order for a particular set of parameters in figures 2a and 2b respectively. We see that the density of fibres increases in the centre of the region, and that the constant initial density loses uniformity temporarily

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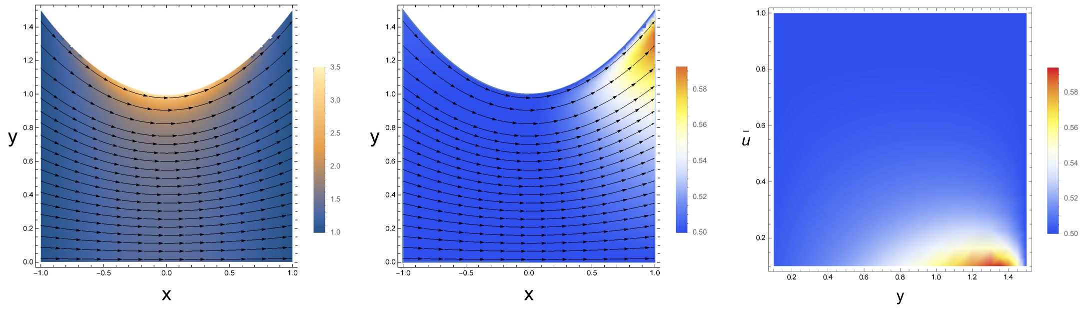
in the interior of the region. We also see that the order of the fibres increases through the region, with the fibres near the upper cylinder becoming more ordered. The dependence of the order parameter, at $x = 1$, on the velocity ratio between the two cylinders, $\bar{u} = u_2/u_1$, can be seen in figure 2c. We conclude from this that a greater velocity difference results in a higher order parameter, which is desirable for producing a web of aligned fibres. This confirms experimental evidence that the relative velocities of the cylinders has a direct effect on the ordering of the fibres.



(a) Distribution of the density of the fibres. **(b) Distribution of the order of the fibres.** **(c) Order Parameter for different velocity ratios, $\bar{u} = u_2/u_1$.**

Figure 2 – Graphs showing how the material moves through the region (along the black arrows) with x being the distance across the region, and y being the distance between the cylinders. The main cylinder is along the bottom and the worker is above. The lengths have been scaled before plotting.

In order to examine two possible mechanisms for why some fibres attach to the worker and some to the main cylinder, we examine the forces acting on a fibre attached to a hook and the forces on fibres throughout the region. We first examine the interaction between the web and the hooks along the cylinders, deriving conditions for when the web remains attached to the hooks. However, in our simple model, this condition is always satisfied, so we consider a different mechanism. We look at the splitting of the web due to a high stress acting orthogonal to the fibre direction and we prescribe a critical stress, which depends on the order of the fibres, that will cause the web to split. We find that a thin layer of fibres follows the worker, with a much larger layer following the main cylinder.

Discussion, Conclusions and Potential Impact

We derived a continuum model for carbon fibres moving through the region between two cylinders in the carding machine. We applied this model to the region between the main cylinder and the worker, and showed how the web of fibres becomes more aligned as the material moves through the region. We considered how the relative velocities of the cylinders affect this alignment, and also described the action of the hooks in the process of carding. We showed that a high velocity difference between the cylinders is desirable for more efficient carding. Using a very simple model, we have been able to predict how the properties of a web of carbon fibres evolve as it moves through one particular section of the carding machine. This model could be used in the future to influence the setup of the carding machine, with the aim of efficiently producing a web of aligned fibres.

Mathilde Poulet, Technical Manager at ELGCF, said:

> *"The model Joe developed confirms that it's possible to mathematically apprehend the way recycled carbon fibres flow within a card set of rollers. The solution provides insight into fibre alignment and the forces encountered during their interactions with wired rollers. This is the first step in quantitatively understanding the variations that may be created during the carding process and how they could be limited, while moving away from time consuming experimental work. This project will be followed with a research program, which will look at the complete carding organ and potentially the rest of the nonwoven production steps."*