CONTROLLING THE SPATIAL DEPOSITION OF ELECTROSPUN FIBRE

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ABSTRACT

Electrospinning process is a simple and widely used method for producing polymeric nanofibres. However, despite its popularity, significant challenges remain in controlling the fibre deposition due to the complex nature of electrospinning process. The process is renowned for its chaotic motion of fibre deposition, also known as the whipping instability. This instability is caused by electrostatic and fluid dynamics interactions of the charged jet and it is partly responsible for the thinning of the fibres into nanoscale diameters. Due to the instability, an electrospinning process typically deposits random orientated fibres in a circular deposition area. Furthermore, there is no control over the location where the fibres land on the collector electrode except that the fibres always travel through the shortest trajectory between the source and the collector electrodes.

In this study, an alternative controlled deposition technique was proposed based on electric field manipulation (EFM). The main hypothesis of this study is that a consistent and repeatable method of controlled deposition can be achieved by using EFM. EFM was achieved by introducing a pair of charged auxiliary electrodes positioned adjacent and perpendicular to the fibre deposition direction. The applied voltage of either direct current (dc) or time-varying (ac) voltage at the auxiliary electrodes act as control to influence the spatial location and size of the deposition area. Samples were produced on black paper substrates and scanned into greyscale images. An image analysis technique was developed to measure the shift and size of the deposition area. A computer simulation was used to calculate the electric field strength and to simulate the behaviour of fibre response based on the trajectory of a charged particle. An image analysis based on greyscale intensity measurement was also developed to examine the uniformity of the deposition area. Finally, fibre characterisation was carried out to examine the fibre morphology, diameter, and orientation based on scanning electron micrographs.

The results from this study showed that EFM can provide a consistent and repeatable control of the deposition area. When the auxiliary electrodes were independently charged with two dc

voltages, it was observed that the deposition area moved away from the most positive electrode. The magnitude of shift of the deposition area was found to increase linearly with voltage difference between the auxiliary electrodes. Furthermore, the aspect ratio of the deposition area (ratio of width over height) decreased linearly with base voltage *i.e.* lower of the two auxiliary electrode voltages. These two controls were found to act independently from each other and can be described as two separate controls *i.e.* voltage difference for spatial location and base voltage for aspect ratio of the deposition area. A similar response was observed in simulation *i.e.* the particle moved away from the most positive electrode. Simulation results also showed that the x-axis component of the electric field (E_x) was responsible for the shift in location and the reduction of aspect ratio of the deposition area.

When the auxiliary electrodes were charged with two antiphase time-varying voltages, continuous scanning of the electrospinning jet was observed producing a wide electrospun fibre mat. It was first thought the smooth oscillation of a sine wave would produce a more uniform deposition pattern compared to a triangle wave, but the results showed otherwise. The inferior uniformity of the sine wave sample was found due to the variability of the jet scanning speed when compared to the constant speed achieved when using a triangle wave. It was also observed that the deposition pattern can be further improved by using two clipped triangle wave voltages. The results open up the possibility for further exploiting the control voltage to achieve the desired deposition pattern.

Two case studies were presented to demonstrate the applicability of the technique in real electrospinning applications. In the first case study, it was demonstrated that the continuous scanning of electrospinning jet was capable of eliminating the stripe deposition pattern which is commonly associated to a multi-spinneret electrospinning system. In the second case study, it was found that the alignment and distribution of aligned fibres in a gap electrospinning system can be improved by using the EFM technique. A new technique was also introduced to produce a multi-layer orientated fibre construct. These application examples showed that the EFM technique is ready for the production of engineered electrospun fibre constructs. This would extend the use of electrospun fibres to applications which is currently limited by geometrical constraints of the fibre constructs.

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CHAPTER 1

INTRODUCTION

Electrospinning is known as a simple, versatile, and scalable method of producing polymeric nanofibres from a solution or melt using electric charge (Reneker and Chun, 1996). Due to their nanoscale diameters, electrospun fibres have been the subject of much study for applications that require a high surface area to volume ratio (Nayak et al., 2012, Greiner and Wendorff, 2007). A wide variety of applications such as filtration, tissue engineering, wound dressing, drug delivery, composite reinforcement, and electronics, have been proposed (Ramakrishna et al., 2005). However, due to the random nature of the deposition process in electrospinning it is difficult to tailor the deposited fibres for specific needs. Despite a number of potential applications, controlled deposition in electrospinning has not been widely investigated. Thus, it is not surprising that the one application in which electrospun fibres have achieved commercial success so far is filtration (Nurfaizey et al., 2012b).

The objective of this study is to develop, validate, and demonstrate a method of controlled deposition of electrospun fibres based on electric field manipulation (EFM). This study is important as it is the first to quantitatively investigate EFM. In addition, developing a successful EFM method would extend the use of electrospun fibres to applications which is currently limited by geometrical constraints of the fibre constructs. To achieve this objective, a series of experiments were conducted to investigate the practicalities of applying EFM in electrospinning. EFM is achieved by introducing charged auxiliary electrodes that are positioned adjacent and in the plane perpendicular to the direction of electrospinning. The application of an electric field *via* the auxiliary electrodes can be used to manipulate the spatial and areal characteristics of a collection of electrospun fibres.

Controlled deposition in electrospinning is used for two main purposes: (i) control of the location of the deposition area in order to produce uniform coverage of electrospun fibres;

and (ii) production of constructs consisting of aligned fibres. For example, a significant challenge in the synthesis of filtration membranes *via* electrospinning is in achieving a spatially uniform deposition of electrospun fibres. The problem of achieving a uniformly distributed collection of fibres is particularly pronounced in the case of a multi-spinneret system due to electrostatic repulsion between adjacent jets that are like-charged (Theron et al., 2005). Various multi-spinneret setups with mechanically moving collectors or spinning heads have been described with the aim of producing uniform coverage of electrospun fibres (Filatov et al., 2007). Aligned fibres on the other hand are conventionally obtained by mechanical means such as rotating drums (Boland et al., 2001), moving spinning heads or collectors (Sun et al., 2006), or using patterned collectors or gap electrospinning (Li et al., 2003).

The methods based on mechanically moving components are complex which require a higher level of supervision and maintenance of the apparatus (Nurfaizey et al., In press). In terms of mechanically collecting aligned fibres, the inertia of the mechanical system imposes an upper limit to the maximum speed of any electrospinning system. Considerable success has been reported in producing aligned fibres using gap electrospinning (Li et al., 2003); however, a major drawback of the process is that it is highly dependent on the geometry of the collector. In addition, residual charges build up on the suspended fibres across the gap have significant influence on the degree of orientation of the fibres (Liu and Dzenis, 2008).

It was suggested that based on an EFM method, controlled deposition of electrospun fibres can be achieved by manipulating the electric field to some degree (Deitzel et al., 2001). Electrospun fibres carry an amount of electric charge during flight, so it is reasonable to expect that using EFM the trajectory of the fibres can be influenced up to the point of impact of the fibre with the collector. However, concern arises from the need to know the relationship between the control variables and fibre response, namely the applied voltages at the auxiliary electrodes and magnitude of deflection of the fibres. The resulting magnitude of deflection of the fibres must be consistent and repeatable in order for EFM to be a useful control system. To the author's knowledge, there have been no previous studies that have attempted to quantitatively describe the response of the fibres to EFM. Finally, the challenge is to demonstrate how the newly developed technique could address practical issues in a large scale electrospinning environment.