AC SPINNING ELECTRODE FOR CONTINUOUS COLLECTORLESS PRODUCTION OF LINEAR NANOFIBER SLIVER

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https://doi.org/10.37904/nanocon.2025.5226

Abstract

Polymer nanofibers are unique materials with a high specific surface area, porous structure, and the possibility of precise morphology control. These properties make them promising materials for medical applications, particularly in tissue engineering, as well as in technical fields including filtration, sensor technology, and composite reinforcement. Currently, nanofibers are mainly used in the form of flat membranes produced by DC electrospinning.

This work focuses on the production of nanofibers using AC electrospinning technology with high productivity and specific morphology. This is achieved, primarily, by replacing a physical and electrically active counter-electrode with a virtual collector. The possibility of using a virtual collector to form nanofiber structures without frictional forces opens the way to the production of advanced nanofiber structures, including low-volume cohesive linear formations.

Previous technologies for producing nanofiber yarns used a supporting core around which the nanofibers were wrapped. In the case of nanofibrous yarn without the supporting core, the method required contact of nanofibers with a mechanical collector during yarn formation, resulting in a higher volume of nanofibers needed to maintain the minimum strength necessary for removal from the collector. As a result, the minimum achievable fineness is limited and the material is excessively compacted in order to be able to transmit the necessary forces.

The presented work describes a method that enables the continuous production of linear nanofiber sliver directly in the virtual collector area of AC electrospinning technology, and without mechanical contact with any physical elements. The resulting unique structure is cohesive, with minimal twisting and no excessive compaction.

The described continuous technology has sufficient production speed for practical use, and the materials produced have application potential, particularly in medicine, where they can support cell cultivation and proliferation.

Keywords: AC electrospinning, linear nanofiber structures, nanofiber sliver, virtual collector

1. INTRODUCTION

Polymer nanofibers are currently employed predominantly as membranes or planar layers deposited on a supporting substrate. This configuration facilitates handling and integration into end products such as filters, wound dressings, or medical textiles [1–4]. From an industrial standpoint, the dominant technology for

producing such planar structures is direct-current electrospinning (DC electrospinning) [5], which is well established, scalable, and delivers reproducible deposition on a solid collector.

The feasibility of continuous production of linear nanofibrous structures by DC electrospinning has been investigated at laboratory scale using a supporting core around which the nanofibrous material was wound [6]. Alternating-current electrospinning (AC electrospinning)-characterized by the absence of an electrically active collector-has enabled straightforward fabrication of composite core yarns with a nanofibrous sheath at high productivity [7].

However, even in these approaches, formation of a linear structure required the use of a supporting core around which the nanofibrous material was wound; the core simultaneously provided the yarn with the tensile strength necessary for subsequent processing, such as knitting and braiding.

The manufacture of pure nanofibrous yarns without a supporting core remains a challenge. DC-electrospinning-based methods have been described, but they generally suffer from low throughput [8], [9]. A recently proposed technology for the continuous production of core-free nanofibrous yarn using AC electrospinning and fiber take-off from a rotating collector, disclosed in patent application 2022-370 [10], achieves favorable strength and high productivity; however, production relies on twisting and compacting a large quantity of nanofibrous material.

To produce a linear nanofibrous material of higher fineness and lower compaction, it is essential to minimize frictional forces during formation, which would otherwise impose a lower bound on the mechanical strength required of the emerging structure. Such a material may find use, for example, in guided cell growth, owing to its open architecture of at least partially aligned fibers that supports proliferation [11], [12]. Our approach meets these requirements by forming a nanofiber sliver in the air, without mechanical contact with other bodies.

The production of a linear nanofibrous material in the air domain of the spinning electrode, without the action of frictional forces, is described in Czech patent CZ 310139. The concept is based on the characteristics of AC electrospinning using a suitable electrode and appropriately tuned electrical parameters of the spinning voltage. In this work, we provide an experimental validation of such an arrangement and report the corresponding processing parameters.

2. PRINCIPLE OF NANOFIBER SLIVER FORMATION IN THE VIRTUAL COLLECTOR REGION

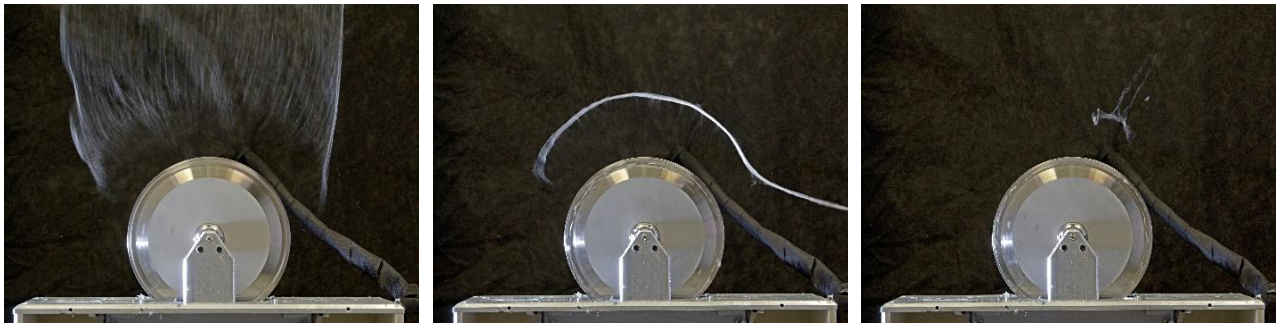
AC electrospinning is a technique in which the electric field acting on a polymer solution overcomes its surface tension at the liquid–air interface, leading to the formation of Taylor cones and subsequent elongation of nanofibers. In contrast to DC electrospinning, where the electric field is established between two fixed electrodes at different electric potentials, AC electrospinning typically employs a single (spinning) electrode supplied with high alternating voltage. Owing to the periodic reversal of the electrode polarity, a sufficiently large potential difference is maintained between the electrode and its surrounding air, and the electric field drives the formation of nanofibers.

The emerging nanofibers move at high velocity in the vicinity of the electrode, along the gradient of the electric field in accordance with the acting electric forces. At a certain distance from the electrode, the fiber velocity drops sharply and the nanofibers aggregate and interconnect into a compact structure - a nanofiber plume - that naturally continues to move away from the spinning electrode (**Figure 1A**). This distance depends on the frequency and amplitude of the spinning signal. It can be assumed that the high nanofiber velocities result from the electric forces, and that the region where the velocity decreases corresponds to the virtual collector, i.e., the location where the electric field force ceases to dominate.

The subsequent motion of the nanofiber plume beyond the virtual collector is governed primarily by the ionic wind generated by the spinning electrode and by the fibers' own kinetic energy. AC electrospinning is unique in that one can identify electrical parameters of the spinning voltage (waveform, frequency, voltage) for which

the electric field is high enough to generate nanofibers, while the spinning energy is sufficiently low that, within the virtual collector region, the nanofibers decelerate and no longer propagate as a plume. They remain within the virtual collector and coalesce into a compact linear formation (**Figure 1B**).

A stable position of this nanofibrous body in the air domain around the electrode is determined by the balance of forces-most notably gravity due to the fiber mass and electrical forces, including ionic wind, interactions with air ions, and forces between oppositely charged segments of the nanofibers. If this linear structure is not withdrawn from the virtual collector, its mass increases until the gravitational force exceeds the restoring forces and the system collapses.



A) B) C)

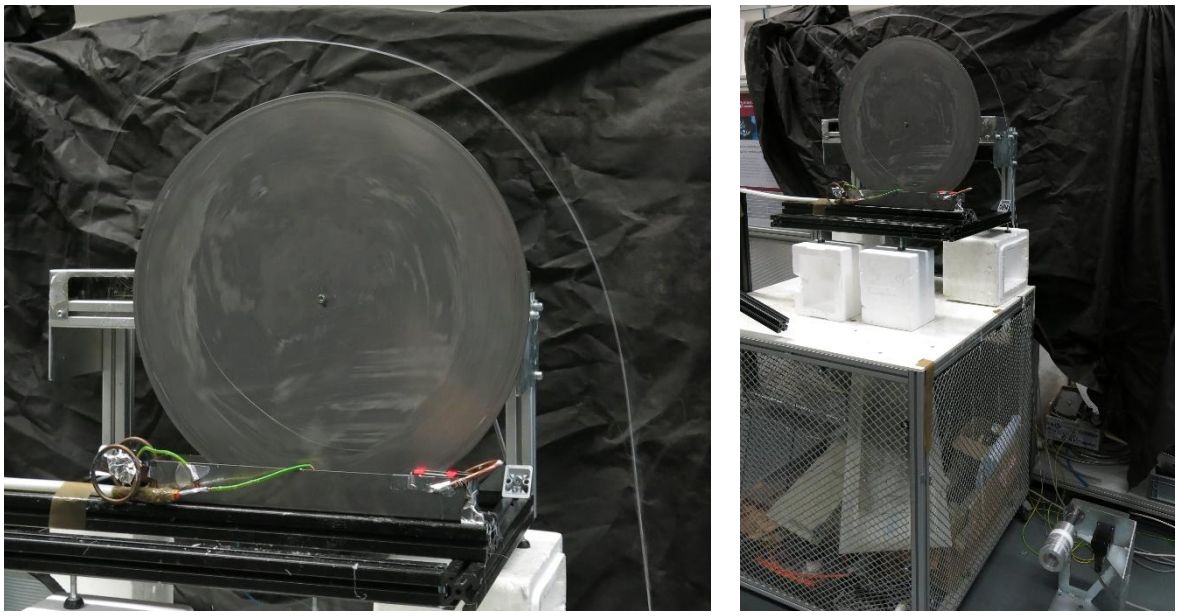
Figure 1 Effect of the spinning-signal parameters on nanofiber motion and on the formation of a nanofiber plume on a spinning electrode of 200 mm diameter. A) High voltage amplitude: prolific fiber generation and formation of a spontaneously moving nanofiber plume. B) Quasi-equilibrium voltage: fiber generation accompanied by aggregation within the virtual collector, from which the structure is withdrawn to the right. C) Insufficient voltage: limited fiber formation.

The ability to withdraw a linear nanofibrous structure from the virtual collector constrains the geometry of the electrode's spinning region. It must be open with free ends, as realized, for example, by a disc or wire (strand) electrode. The linear nanofibrous structure is then taken from the virtual collector by pulling one of its free ends along its length, thereby producing a continuously manufactured nanofiber sliver.

3. SPINNING ELECTRODE AND SETUP

For the fabrication of the nanofiber sliver described in this work, a disc electrode with a diameter of 500 mm and a thickness of 1 mm in the spinning region was used (**Figure 2**). The electrode rotates about a horizontally oriented axis and, with its lower segment, is immersed in a bath of polymer solution, which ensures a continuous supply of solution to the spinning region while simultaneously washing off residual, unspun solution and any adhering nanofiber fragments.

On the disc electrode, nanofibers and the nanofiber plume form within a narrow, planar zone with open edges, which makes this geometry highly suitable for producing a nanofiber sliver. The domain of supercritical electric-field intensity-where fibers are generated-extends over nearly the entire circumference of the disc, with the exception of the lower sector shadowed by the solution reservoir. The electrode diameter is a critical parameter: as the diameter increases, the length of the spinning region and thus the overall productivity increase as well. However, a larger diameter also imposes stricter demands on manufacturing accuracy and geometric runout of the electrode and increases the challenge of uniformly supplying the electrode circumference with polymer solution.



A) B)

Figure 2 Disc electrode of 500 mm diameter. A) Detail view of sliver production. B) Overall view of the experiment; the winding unit is visible at the lower right.

The spinning voltage applied to the disc electrode is generated by an OWON AG1022 function generator and amplified by a TREK 50/20 high-voltage amplifier. The polymer solution is polyvinyl butyral (PVB; 10 wt% Movital B60H in 98 vol% ethanol). The produced nanofiber sliver is continuously withdrawn and wound at a constant linear speed.

4. RESULTS

The described system enables production of a nanofiber sliver at linear speeds of up to 40 $m \cdot min^{-1}$ with a fineness of 10–20 tex (**Table 1**). A quasi-steady operating regime was identified for a rectangular waveform at frequencies of 20–50 Hz and an effective (RMS) voltage of 37.5–45.0 kV. SEM images of the sliver (**Figure 3**) confirm its nanofibrous character, a high degree of fiber alignment, and an open architecture without significant defects. The tensile strength is low, but sufficient for careful handling, winding, and unwinding.

Table 1 Spinning parameters

sample	**frequency (Hz)**	**voltage (kV)**	**winding speed ($m \cdot min^{-1}$)**	**fineness* (tex)**
1	30	37.5	15	20
2	**20**	40	15	16
3	**50**	37.5	25	20
4	30	40	35	10
5	30	45	40	16
electrode: disc; diameter 500 mm, thickness 1 mm			**waveform:** rectangular	
			polymeric solution: PVB	
speed of the electrode: 15 rpm				
* fineness was measured on 5 m samples				

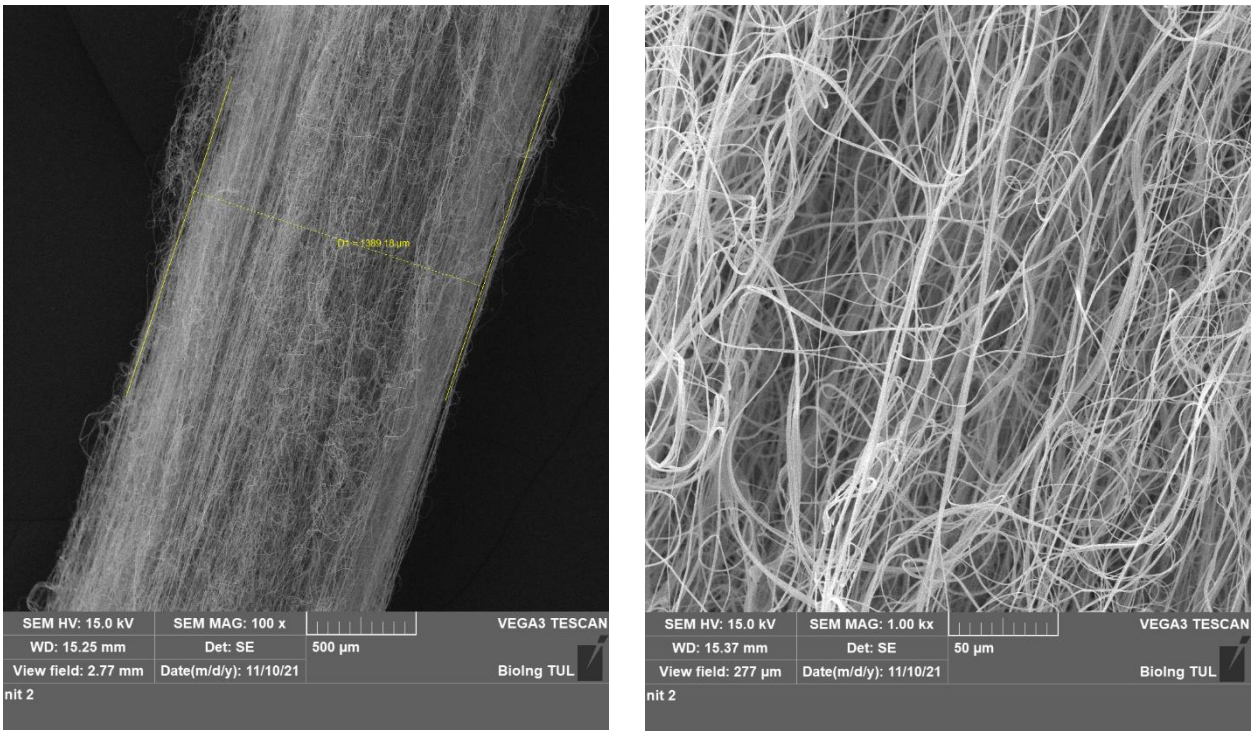


Figure 3 SEM images of nanofiber sliver (sample 2 according to table 1).

5. DISCUSSION

The force – balance equilibrium of fibers within the virtual collector primarily depends on an appropriate combination of the spinning-signal frequency, voltage, and waveform, which are also the key parameters governing electrode productivity. For a given frequency and waveform, the admissible voltage window is typically narrow, and the required voltage decreases with increasing frequency. As a result, the productivity per unit length of the spinning region is approximately constant across different electrical settings; therefore, to increase the overall electrode throughput, one must increase the electrode size, i.e., the length of the spinning region.

The gravitational force acting on the nanofiber sliver-and entering the force balance within the virtual collector-is not uniform along its length; it increases in the take-up direction as the sliver's linear mass accumulates. In the case of a disc electrode with a horizontal axis of rotation, the orientation of the gravity vector relative to the resultant electrical force (which can be assumed to be close to the electric-field gradient, i.e., approximately radial to the electrode) is not constant. This variation in relative orientation further reduces the stability of the sliver during formation.

6. CONCLUSSION

A spinning electrode capable of producing a compact linear nanofiber sliver of very high fineness, entirely without mechanical contact with any bodies in the spinning zone, was designed and tested. The experiments confirmed the nanofibrous nature of the sliver, a high degree of fiber alignment, and a mechanical strength sufficient for winding, unwinding, and careful handling. The proposed apparatus shows clear potential for continuous industrial production of a nanofiber sliver.

Future work will focus on optimized spinning-electrode designs to further increase productivity, on bundling (coalescing) slivers from multiple electrodes, and on developing an electrode configuration that minimizes

longitudinal variation in the resultant force acting on the sliver during its formation within the virtual collector region.

Owing to its open architecture and high degree of fiber parallelization, the nanofiber sliver is particularly promising for medical applications, including cell growth and guided cell culture, where it can support cell adhesion and proliferation.

ACKNOWLEDGEMENTS

This publication was written at the Technical University of Liberec as part of the project with the support of the Specific University Research Grant 2024-5443.

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