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Review Article

A Study on Microfluidic Spinning Technology (MST) Used for Micro Fibre Fabrication

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Abstract

Functional polymeric micro/nanofibers have gained considerable interest as promising materials for the structures that are potentially beneficial in lot of application areas as they possess excellent characteristics such as large surface-area-to-volume ratio, incredibly small pore dimensions etc. Microfluidic developments have currently shown a huge amount of opportunities as revolutionary approaches to create microfiber. By carefully regulating the flow and reaction kinetics in microchannel chip, microfluidic-spinning technology can be applied to generate fibers with tailored characteristics and polymorphic structures. However, this paper features the basic mechanism of micro-fiber production by microfluidic spinning Technology (MST) as well as the principle of Elcectro-Microfluidic Spinning Technology (EMST). Besides, core-shell fiber production by MST is also described in brief. Finally, the advantageous features, application areas and challenges of MST are reviewed briefly in this paper.

Keywords: Micro-Fiber; Microfluidic; Spinning

Introduction

Microfluidics has gotten a lot of attention from scientists and engineers in a variety of fields [1]. Microfluidics is described as the design or application of devices that apply fluid flow to channels that are smaller than 1 millimeter in at least one dimension [2]. It is also named as miniaturized total (chemical) analysis system (μTAS) [3]. To create microscale liquid structures, this method allows for versatile and precise manipulation of the flow and dispersion of several liquids in microchannel [4]. It's a promising method for using small amounts of materials in a variety of applications, including biomedical and energy devices [5].

Micro/nano fibers are ubiquitous, whether in nature or modern industry [6]. Polymeric fibers are gaining popularity due to their unique properties, including a high surface area to volume ratio, versatility in surface functionalities, and superior mechanical performance (e.g., stiffness and tensile strength) when contrasted to any other known material type [7]. Energy conservation, tissue engineering, pollutant separation and wound healing are only a few of the applications for functional microfibers [4]. Encapsulating cells on microfibers, for example, provides a simple three-dimensional (3D) model for cell culture and the development of complex tissues [8]. Spinning methods, however, have received a lot of attention among the various technologies for producing polymer fibers [9].

Microfibers are being made from a variety of materials using traditional fabrication methods such as electrospinning and wet spinning, but producing microfibers with controllable internal microstructures remains a challenge [4]. The majority of microfiber production techniques have a homogeneous chemical composition and structures that vary significantly from those found in human tissues. Other spinning methods' limitations have prompted researchers to develop new techniques for producing fibers with a topographical architecture that more closely resembles the complex structures and functions of living tissues or organs [10]. Furthermore, they are generally compatible with a limited range of materials and often necessitate a lengthy processing method, both of which severely limit their applications [11]. Microfluidic Spinning Technology (MST) has recently risen to prominence as a simple method for creating orderly diverse structures, controllable compositions, and well-organized functions [12].

Knowledge of technology and engineering is the fuel for creativity and success. A spinner must therefore be technologically aware, efficient, flexible, and cost conscious. From this perspective, it is attempted to make an overview of mechanism of microfluidic spinning technology (MST). After that, microchannel chip formation method, as well as the advantages of this spinning system for microfiber production have been described. Besides, mechanism of co-axial and electro microfluidic spinning system are also given briefly in this paper.

Microfluidic Spinning Technology (MST)

Microfluidic spinning technology (MST) is a technique inspired by the natural phenomenon of spiders or silkworms spinning silk [8]. It can also be stated as the type of Solution Blow Spinning (SBS) system. However, microfluidic spinning (Figure 1), a combination of wet spinning and microfluidic technology, has been used to produce microfibers with unique structures [13].

Basic mechanism of microfluidic spinning

This spinning method is based on the principle of micro-scale fluid dynamics. Generally, the two streams flow into the microfluidic system from two different microchannels to meet finally at a junction [11]. The use of a suitable central and shear fluid pair is pivotal for

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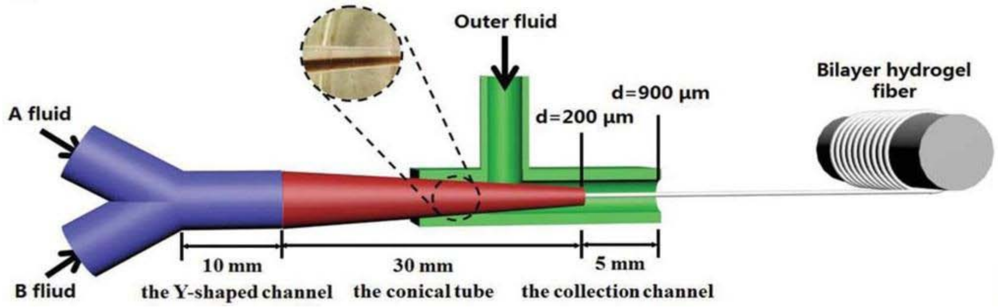

Figure 1: Microfluidic Spinning Technology (Zhou M, Gong J, Ma J. Continuous fabrication of near-infrared light responsive bilayer hydrogel fibers based on microfluidic spinning: e-Polymers. 2019; 19(1): 215-224. https://doi.org/10.1515/epoly-2019-0022 [14]).

effective chemical spinning approaches [15]. Microchannels have small dimensions, so flow is laminar and there is no turbulence [11]. Fluidic gravity and inertia, as well as fluid viscosity and surface tension, all affect laminar flows in microchannels [12]. Depending on the flow rates and physical/chemical properties of the liquid phases, jets or emulsion droplets may form at the microchannel junction. However, the creation of stable continuous jets in a microfluidic system is aided by the laminar flow behavior of liquids in a microchannel. Jet generation is usually accomplished using microfluidic devices with cross-junction geometry and co-flow geometry. The surrounding liquid phase can hydrodynamically shape the center liquid phase into a cylindrical jet [4]. The 3-D coaxial sheath flow stream surrounds the sample flow due to micro scale phenomena. During coaxial flow creation, cylindrical channels make it easier to manage the flow parameters [15]. The sheath fluid works as a lubricant to aid fiber extrusion and, in some situations, as a crosslinking solution, while the core fluid contains a polymer precursor solution [9]. PVA is a good sheath fluid material in general since its viscosity is easily adjusted and it is non-toxic. Alginate, PLGA, and chitosan are the most commonly used central fluid components in ECM and biomedical applications. Materials used in microfluidic spinning are shown in Figure 2. However, the flowing central flow should harden as quickly as possible during fiber production adopting microfluidic-spinning techniques [15]. During the fiber formation process, an appropriate solidification approach should be chosen based on the fluid composition [9]. Depending on the materials employed, solidification processes include UV-induced polymerization, phase inversion, and ionic or chemical cross-linking [11]. Finally, microfibers are supposed to be taken on a collector at the end.

Microfluidic system-fabricated fibers are often smaller than wet spun fibers but larger than electrospun fibers [16]. The fiber diameter in this spinning system ranges from 400nm to 500µm [9]. By altering the flow rates of the liquid phases as well as the microchannel dimensions of the injection and collection capillaries, the diameter of the microfiber may be precisely and flexibly tuned [4]. The fiber diameter may indeed be affected by the rotational speed of the collecting roller, which applies an external elongation force on the fiber [16].

Multiphase flows, coaxial flows, and parallel flows can be employed to fabricate complicated fiber structures thanks to the availability of laminar flows [17]. Many factors influence the fluid streams in these microchannels, including the composition of various fluid phases and their viscosities, interfacial tension, surface energy, and device geometry [11]. For example, the core and sheath fluids have to be matched in terms of viscosity in order to maintain the shear force at the fluid/fluid interface in the stable flow regime. Furthermore, there is always the chance of microchannel clogging due to unexpected shear force, which is caused by a mismatch between the fluid characteristics or an inaccurate flow rate ratio [5]. Matching the viscosity ratio of the central phase and the sheath phase, their flow ratio has the potential to deform the co-flow into a buckle or spiral shape, and even contract as a tube attached to the inner wall of the collection channel. These adaptable flow shapes can subsequently be used to make various 3D structured microfibers [11]. Different types of designs can also be engraved onto the surfaces of the fibers along the longitudinal direction, depending on the geometry of the channel cross-section. The solid cylindrical shape is, nevertheless, the most popular shape of microfluidic-spun fiber. Thin and flat tubes can be employed as platforms for spinning flat fiber continually. Microfibers with grooved surfaces can be spun using longitudinal grooves on the inside surfaces of cylindrical channels [15].

With the shearing of outer continuous flow in microchannels, laminar jets may generally obtain stable interfaces. Furthermore, by matching the viscosities and flow rates of two liquid phases, a coiled jet can be created in the microchannel based on the effect of liquid rope coiling. The diameter of the laminar jet and the pitch of the coiled jet may be precisely regulated by adjusting the microchannel dimensions and flow rates. These adjustable jets can be used as templates for continuous microfiber synthesis. Microfibers having a helical structure and circular cross section can be produced by quickly solidifying coiled jets in a microfluidic device [4]. Helical microfibers have recently received a lot of attention because of their extraordinary structure and spring-like responsiveness [18]. To manage multiple liquid phases, a sequential configuration of microfluidic geometries is usually necessary for the creation of complicated jets. To create a tubular jet, the laminar jet created in the first geometry can be encapsulated in another jet developed in the second geometry. Functional microfibers can be fabricated using quick solidification techniques and integrating functional components into laminar jets of microfluidics. Moreover, functional hollow microfibers can be generated using tubular jets from microfluidics as templates by inserting functional components into the outer sheath phase of tubular jet. Microfluidic-fabricated functional microfibers with solid and tubular architectures are intriguing for biological applications such as tissue engineering [4]. However, microfluidic devices for spinning have been commercialized by some enterprises (e.g., MicroFIT; Micronit), which is extremely advantageous for the

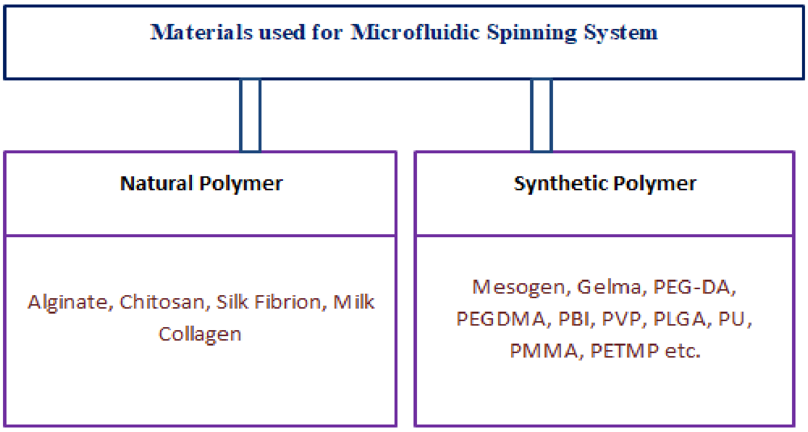

Figure 2: Materials Used for Microfluidic Spinning.

practical purposes of microfluidic-spun fibers [9].

Electro-microfluidic spinning technology (EMST)

Due of the chaotic motion and bending instability of high-charge solution jets, it is difficult to generate highly orientated NFs using the conventional electrospinning approach. Xie et al., on the other hand, proposed a new Electro Microfluidic Spinning Approach (EMST). The novel 1D fiber spinning technology combines the benefits of MST, such as simplicity, efficiency, and flexible controllability, with the advantages of electrospinning, such as smaller fiber diameter, large specific surface area, and high yield, to establish a functional nanofiber preparation method with a variety of morphologies and improved physicochemical properties. A zigzag drum collector was devised to substitute the plain drum collector and realized the aligned NFs collection in order to acquire highly ordered fibers. The applied voltage and spinning solution flow rate can control the degree of alignment and diameter of aligned NF. The high-speed spinning zigzag collector's gear teeth offer enough physical mechanical traction to stretch the unstable small polymer jets induced by a high voltage electrostatic field into orderly parallel NFs. Furthermore, the "zigzag" collector can be considered numerous of gap electrode collectors. As a result, the synergistic effect of irregular electric potential and mechanical traction helps nanofiber align [19].

Core Shell (C/S) Microfluidic Spinning

MST has recently been demonstrated as a viable and promising technology for producing microscale core–shell fibers. In microfluidic channels, core–shell laminar flows composed of a curable core fluid and a polymerizable shell fluid occur spontaneously with the help of the outer noncurable sheath flow [12]. Various core components of microfibers, such as hyaluronic acid laminar flows, biological cells, ECM protein, silk fibroin linear array, and oil micro droplets, can be wrapped by an alginate hydrogel layer as an outer protective shell. Core-shell alginate microfibers, for example, can be generated in parallel or coaxial laminar flows. In a rectangular polydimethylsiloxane (PDMS) microchannel with a consistent thickness, parallel laminar flows are managed to create. A typical microfluidic device in this situation would have three inlets and a long gelation microchannel. Coaxial laminar flows, on the other hand, necessitate a microfluidic device with coaxial geometry. An inner tapered glass capillary and an outer cylindrical or square tube constitute a coaxial microfluidic device [20]. Hollow tubes, flat fibers, Janus structures, spiral curls, and bamboo-like architectures can all be made utilizing coaxial laminar flows [8]. However, a core-shell hydrogel microfiber was produced using a multi-coaxial microfluidic device [20]. Human induced Pluripotent Stem (iPS) cells were encapsulated (Figure 3) and cultured within the core portion of core-shell hydrogel microfibers produced by MST [21].

Advantages and limitations of MST

There are numerous advantages to microfluidic devices that allow for continuous extrusion of polymeric microfibers [15]. Unlike alternative spinning processes, MST employs well-designed microfluidic chips to integrate microfluidics with chemical reactions, allowing for simultaneous production and functionalization of fiber materials. MST is a robust platform and promising possibility for the fabrication of sophisticated micro/nanoscale fibers with numerous functions and significant applications [12]. The capacity to spin numerous fibers in parallel through multichannel arrays, rapid prototyping, and a simple procedure are all advantages of microfluidic devices for fabricating fibers [22]. Furthermore, by modifying the geometric characteristics of the microfluidic channels, more intricate and intriguing structures such as string-of-beads, circular, flat, grooved, hollow, anisotropic, core–shell, Janus, triple, and heterogeneous structures may be easily customized [19,12]. A novel coaxial microfluidic method for spinning helical Ca-alginate microfibers was devised based on the "liquid rope-coil effect" and demonstrated their potential applications in vascular tissue engineering [23]. In the microfluidic spin approach, however, generating alginate microfibers with complicated compositions and morphologies is a hotspot [20].

One of the most useful aspects of this spinning process is the ability to build 3D fibrous structures using reeling, weaving, and direct writing, which is particularly useful in the construction of scaffolds [9]. Most natural polymers that may be spun into fibers utilizing microfluidic spinning are made in an aqueous environment, which prevents denaturalization during the production process [15]. The small quantities (50uL) required for fiber production are another advantage of microfluidic fiber fabrication [17]. The fabrication

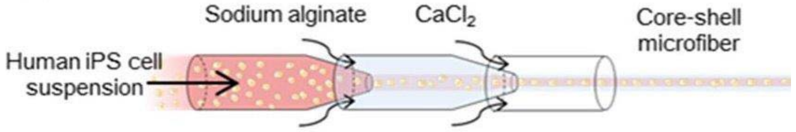

Figure 3: Cell-encapsulating core-shell hydrogel fiber was formed in coaxial microfluidic device (Ikeda K, Nagata S, Okitsu T, et al. Cell fiber-based three-dimensional culture system for highly efficient expansion of human induced pluripotent stem cells. Sci Rep. 2017; 7: 2850. https://doi.org/10.1038/s41598-017-03246-2 [21]).

process can be carried out in ambient condition [19]. Microfluidic spinning also has a low sensitivity to operating factors and so has a high degree of reproducibility [8]. MST has demonstrated to be an effective method for producing hydrogel fibers with immense promise in tissue engineering [14,24].

Unlike electro-spinning or melt-spinning techniques, microfluidic spinning technologies appear to be safe for cell encapsulation applications [15]. Microfluidic spinning has recently emerged as one of the most appealing approaches for fabricating protein fibers [25]. Several studies have been published on the microfluidic spinning system's ability to produce protein-based biological fiber. The protein spinning solution and the Glutaraldehyde (GA) solution were injected into the two channels (i.e., inner and outer) of the microfluidic device to produce biological fiber [25,26]. Microfluidic fabrication of milk collagen, chitosan, alginate, and spider silk fibers was also successful. As a result, this technique is applicable to the production of protein fibers from a wide range of proteins found in nature. Furthermore, such protein fibers have excellent mechanical strength due to their intrinsic biocompatibility [25]. Free-standing microfluidic-spun fibers can be implanted in the body. Through guided culture, such fibers have been used to align myoblast, cardiomyocyte, and neuron cells [15].

Any sensitive biological materials, including cells, can be placed into the fiber without losing function because the fluid is not exposed to high voltages, high temperatures, or high stresses. The cells are not physically or chemically harmed by the spinning environment [15]. Complex, pure chitosan fibers appropriate for cell culture were produced without chemical additions employing Microfluidic-Spinning Technology (MST). ECM proteins and pancreatic islet cells were used to generate core-shell fibers. In diabetic mice, these fibers were implanted to restore normal glucose levels [17]. Grooved microfibers are good for inducing cell alignment; Hollow microfibers have a lot of promise for simulating blood vessels and the tumor microenvironment [18].

Despite the obvious benefits of microfluidic spinning, there are still a number of obstacles to overcome. The incapacity of the microfluidic process for generating fibers to evolve into a high speed is a limitation [27]. Due to the challenges in building nanoscale microfluidic chips and injecting fluids into the channels, microfluidic spinning poses a considerable difficulty. Furthermore, the extremely short time necessary for fiber solidification is a significant hurdle [9]. Clogging might be an issue for reliable continuous production of long fibers due to the tiny feature size of microfluidic channel geometries [17]. Because of the mechanical traction force constraint, preparing nanoscale fibers with the MST technology is challenging. Furthermore, fiber mechanical characteristics are still unsatisfactory [19].

Conclusion

Microfluidic Spinning Technology (MST) uses well-designed microfluidic chips to integrate microfluidics with chemical reactions, allowing for simultaneous preparation and functionalization of fiber materials. To produce microfibers for biological applications, a suitable solidification method is needed as some solidification approaches have limitations. Microfluidic spinning methods have many benefits over the existing spinning methods, including the ability to apply them to a variety of materials. One of the greatest advantages of microfluidic techniques is their high scalability for controllable development of complex liquid systems with diverse structures for fabricating micro/nanoscale fibers. Microfluidic spinning innovations are gaining traction as cutting-edge techniques in tissue engineering and cell biology. However, MST with number of superior advantages that make it a viable option for producing micro/nanoscale fibers. In summary, spinning mechanism of micro fiber fabrication by microfluidic spinning technology, advantages and limitations of this system for textile application described in this study can be utilized for future study.

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