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TEXTILE ENERGY STORAGE DEVICES – BATTERIES

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Abstract: *We are in the age of digital technologies, and the continuous growing demand for wearable and portable smart devices leads us to replace the conventional energy storage devices necessary for power supply with new ones that fully meet the needs of consumers by meeting specific conditions: be flexible, adaptable to deformation, have a long service life, be light, thin, sometimes invisible and with adaptable shapes and small dimensions. In addition, ensuring safety, wearing comfort and the use of non-toxic and eco-friendly materials are other current concerns that pave the way for further successful implementation of these devices. Among the energy storage technologies, batteries are the oldest, most common, and widely accessible form of storage. Technology and materials have evolved, so we have the most varied and sustainable resources for the manufacture of innovative batteries that meet all the requirements mentioned above.*
In this regard, this paper briefly presents a new possibility for the realization of energy storage devices, namely using textile materials. Thus, the aspects related to the component materials, the design features, and some technologies for the construction of textile-based batteries are approached. Several research teams addressed this matter, developing either fibre-shaped batteries or, more complex, fabric-based alternatives. Also, the encountered technical difficulties in developing such devices are discussed.

Keywords*: wearable technology, energy storage, textile battery, deformability, design strategy*

1. INTRODUCTION

The battery industry is changing very fast given the rapid progress of new designs, production methods and modified chemistries. Also, the miniaturization and digitalization of consumer electronic products are two directions that contribute to changing the design and performance of these batteries.

The growing need for batteries in the digital age of laptops, smartphones, tablets, smart electronics, electronic textiles, etc. will drive the global consumer battery market to reach $50 billion by 2025 [1]. As the wearable electronics market expands and traditional battery technologies struggle to achieve flexibility, foldability, stretchability, thinness and lightweight properties, new energy storage solutions with innovative and modern form factors that can meet these criteria are needed [2]. In this regard, important steps have been taken in the development of functional energy storage textiles, for truly wearable and portable smart devices. Thus, textile fibre-shaped batteries are one step closer to this goal and have excellent new features that can enhance their applicability.

As structural deformability is being one of the most important demands for these new batteries, there are two general approaches to introduce it into batteries:

- replacing intrinsically stiff materials by soft and bendable compounds;
- processing of the stiff materials into structures that are flexible [3].

2. TYPES OF TEXTILE BATTERIES

A battery is a device that can store chemical energy and convert it through a series of electrochemical reactions into electricity. In general, the architecture of a battery is made up of several elements, such as two electrodes (anode and cathode), each with a current collector, that sits on opposite ends of the battery, and a separator between them. While these items are common to all batteries, the difference lies in the choice of constituent materials [4].

Two approaches are considered for the construction of a textile battery, namely:
(1) the one-dimensional (1D) approach, in which all battery materials are stacked into a single fibre, yarn, or cable (fibrous structure);
(2) the two-dimensional (2D) approach, in which the available textiles (woven, knitted, nonwoven) are incorporated with active materials (planar structure) [4].

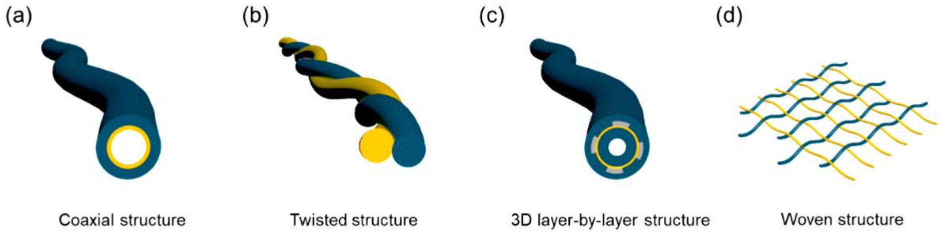

Fig. 1: Schematics of batteries structures made of textile materials: (a–c) 1D electronic fibres and (d) 2D electronic textiles [5]

2.1 Fibrous structure-based battery

Fibrous materials (fibres, filaments, yarns) represent a promising option to manufacture batteries attributing to their superstructure with large surface area, lightweight, good flexibility, cost-effectiveness, and the ability to sustain complex deformations. In addition, their potential for mass production and in many different forms (solid, hollow, core-shell, or hierarchically porous structure) due to the various textile technologies makes them suitable for building batteries [6].

When designing a fibrous battery should be considered that the essential components of these batteries (electrodes, electrolytes, and separators) and their structures to be compatible.

Since the electrodes are being the core elements in a battery, they should possess the intrinsic ability to bend, the most important factor, therefore ideal materials need to be chosen. So far, several materials and structures have been studied for the manufacture of electrodes, such as metal wire-based electrodes, carbon fibre-based electrodes, carbon nanotube fibre-based electrodes, graphene fibre-based electrodes or film-based electrodes (e.g carbon nanotube sheets) [7]. Although carbon materials have outstanding electrical and mechanical properties, the production of CNT fibres is extremely expensive, and often requires using expensive technologies [8].

The electrolyte is the element that separates the electrodes. Electrolyte performance has a direct impact on the working temperature, safety, cyclability, and cell capacity of the battery [9]. To improve the performance of a battery, a large number of electrolytes have been developed, primarily categorized as liquid-based electrolytes and solid electrolytes.

Liquid electrolytes can be further classified into nonaqueous electrolytes (carbonate esters and ethers) and aqueous electrolytes. The non-aqueous electrolytes hold many advantages like high ionic conductivity, low viscosity, high stability, and relatively low cost, but they often pose potential safety hazards resulting from electrolyte leakage and flammability [10]. Instead, the aqueous types are non-flammable and attractive for batteries with high power density. They possess highly ionic conductivity and are also low-cost. But they face some major problems by affecting the metal electrode by corrosion, passivation, hydrogen evolution, and dendrite formation, they have limited water thermodynamic electrochemical window and their performance at low temperatures is limited by the freezing point [11].

Solid-state electrolytes can be divided into polymer-based (organic) electrolytes and inorganic electrolytes. Among them, gel-polymer type (GPE) is a more desirable electrolyte formed by incorporating an organic liquid electrolyte in a polymer matrix. It is safe, has high thermal stability, and low volatile nature [12]. It benefits from a better ionic conductivity than that of solid-polymer (SPE) types and is very close to the values observed for liquid electrolytes. The most common polymers used to prepare GPEs are polyacrylonitrile (PAN), polymethylmethacrylate (PMMA), polyvinylchloride (PVC), and polyvinylidene fluoride (PVDF) [13]. One of the significant drawbacks of GPEs is insufficient mechanical strength, due to the lack of rigidity in their matrix, which limits their application [12]. Besides, when the incorporation of fillers is achieved, a new class of electrolytes arises, the composite-polymer electrolytes (CPE) [9].

The first battery made into a fibre shape was the lithium-ion battery (LIB), because of its easy fabrication. But the low energy density limited its real applications [14]. In addition, until now numerous other fibre-shaped batteries have been also developed, according to the main materials used for making the electrodes: zinc-ion battery (ZIB), zinc-air battery (ZAB), lithium-air battery (LAB) (table 1).

Table 1: Different types of fibrous batteries

Battery type	Shape	Anode	Cathode	Electrolyte	Voltage	Cycle life	Ref.
LIB	twisted	$Li_4Ti_5O_{12}$ (LTO)-composite coated onto a steel-filled polyester conductive thread (SPCT)	$LiFePO_4$ (LFP)-composite coated SPCT	LiPF6 and polyethylene oxide (PEO) solid-state electrolyte	~ 2.3 V	>30000 bend-release cycles	[8]
ZIB	coaxial	Zn wire	MnO2 coated carbon wire	GO flakes–embedded PVA hydrogel	~ 90 mV	>1000 charging/ recharging cycles and >500 twisting cycles	[15]
ZAB	spring	Zn wire spring	Teflon plate covered with aligned and cross-stacked CNT sheet	PVA-PEO-KOH hydrogel electrolyte	1.0 V	30 discharge/ charge cycles and 100 bending cycles	[16]
LAB	coaxial	Li wire	Aligned CNT sheet	Gel electrolyte	2.45 V	100 cycles	[17]

2.2 Fabric-based batteries

To develop fabric-based batteries different approaches have been used:

a) stitching a few fibre-shaped batteries into a piece of existing fabric;
b) fabricating loosely woven - knitted fabrics with fibre-shaped battery units [18].
c) using printing technology to add a proper layer with demanded properties to a textile layer, woven or knitted;
d) coating fabrics that are stacked together layer by layer.

By integrating multiple fibre batteries in fabric structures, an increased storage capacity will be obtained, thus providing a long working time for future wearable electronics [19]. Realizing soft woven/knitted energy textiles is still challenging due to the generally large diameter of the battery fibres with complex layered structures, as well as the increased mechanical modulus, affecting further their processability [18].

Printing technologies are much more appropriate to produce batteries including textile substrates, because of many advantages: design freedom, a wide variety of materials, textile breathability and flexibility, ultra-thin, lightweight, environmental safety and low cost. There are two most common printed battery designs: stack or sandwich, and coplanar or parallel (two electrodes placed in a side-by-side arrangement) architectures. Also, two chemistries are very used for the manufacturing of printed batteries: lithium-ion and zinc–manganese dioxide chemistries [20].

Further are exemplified some approaches to manufacture fabric-based batteries, which are based on unusual types of electrolytes that support the production and storage of energy.

Sweat activated fabric-based battery

Recently, Gang Xiao et al. developed a cotton-yarn-based sweat-activated battery (CYSAB) with a three-segment structure, in which carbon-black-modified, pristine yarn and Zn foil-wrapped segments were prepared to serve as the cathode, salt bridge, and anode, respectively. This type of battery can be rapidly activated upon electrolyte absorption. The ion concentration, the infiltrated electrolyte volume, and evaporation rate are three key factors that influence its performance.

The CYSABs were woven into fabrics and connected in series and parallel configurations to produce an energy supplying headband, which was activated by the sweat eliminated during physical activity to power light-emitting diode headlights. Electricity generation from the CYSAB greatly relies on the wicking of the electrolyte solution into capillary channels between the fibres and the migration of ions in the aqueous environment. Thus, it is demonstrated the ability to use these batteries in health monitoring [21].

Bacteria activated fabric-based battery

Bio-based batteries can be developed by using enzymes or microorganisms to scavenge biochemical energy from the wearers' body fluids such as sweat, saliva, blood, and tears. This type of biological battery can be the most suitable power source for wearable-health monitoring systems [22]. This approach was recently studied by a research team at the State University of New York-Binghamton. They developed an entirely textile-based, bacteria-powered biobattery that could one day be integrated into wearable electronics. It was used a single-layer fabric comprised of 92% polyester and 8% spandex. The structure of the battery consisted of the anode and cathode placed in a single reaction chamber with no separating membrane. The single-chamber was formed by screen printing an anodic paste (PEDOT:PSS) on one side of the fabric and then a cathodic paste (PEDOT:PSS modified silver oxide) on the other side while controlling the pastes' penetration into the material. The anodic reaction chambers were engineered to have electronic conducting paths, and microfluidic reactors for the bacterial cells and the silver oxide/silver were used as coupled solid-state oxidant cathodes [22].

Fruit-based textile battery

Fruit-based gel electrolytes are a promising approach to produce batteries because natural fruits contain abundant ionic content. By using citric acid extracted from citrus juices and mixing it with gelatine or starch, flexible, transparent and environmentally friendly gel electrolytes can be obtained. These electrolytes can be sandwiched between metallic fabric-based electrodes to create energy storage devices [23] [24].

Compared with planar batteries, the designing and fabrication of fibre-shaped batteries (FBs) encounters some problems (Fig. 2). Mainly, the FBs devices should avoid the short-circuiting and leakage of the electrolytes, in the processes of work and deformation. The safety, convenience, and durability of FBs are important directions for their practical applications in the future [25].

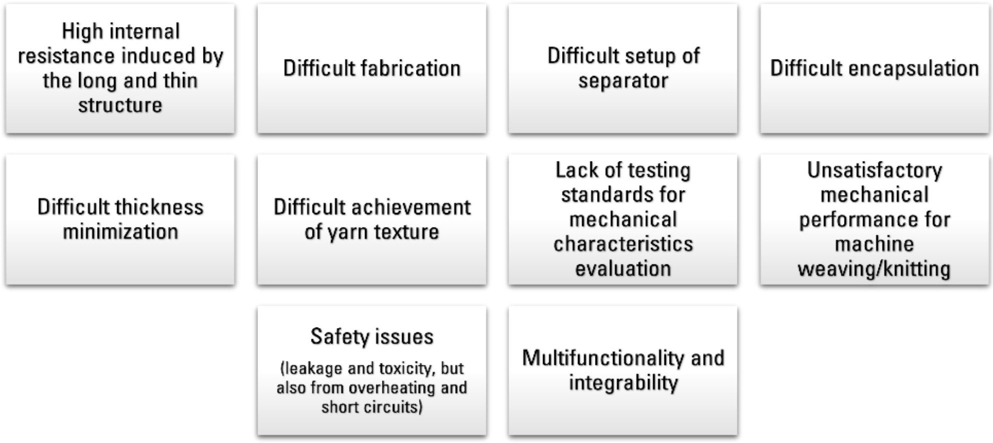

Fig. 2: The technical difficulties encountered by the 1D textile-based batteries for future wearable applications [18]

3. CONCLUSIONS

Wearable devices are used both for personal and work-related purposes in many different industries like healthcare, sport and fitness, fashion, security, retail, construction, logistics and transportation, etc. because of the multiple advantages that they bring: health monitorization, stimulation to have an active life, safety, data storage, information and so on.

We need efficient fabrication strategies for the storage energy technology to obtain functional and smart wearable devices for a better user experience and with improved performances on many different levels: mechanical properties (flexibility, bendability, rollability, stretchability, foldability, etc.), high rate/cycle capability, thickness, durability over time, stability and biocompatibility, interactivity, adaptability and aesthetic design.

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