ADDITIVE MANUFACTURED FLEXIBLE TEXTILE-BASED SENSORS: A BRIEF OVERVIEW

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Abstract: *Additive manufacturing technologies have a great potential for use in the manufacture of flexible sensors and in recent years, rapid research advances have been achieved in this field. Moreover, by combining textiles with printing technologies, novel sensing structures can be developed, eliminating the disadvantages of rigid sensors. These sensors are in great demand in various applications from the field of wearable e-textiles, such as sports, rehabilitation, and in medical tasks like vital sign monitoring. Printing makes possible to design patterns with complicated structures that could not be possible with the traditional weaving techniques, for example, because of the lack of precision. This also allows the use of a wide range of materials with advanced properties. Flexible sensors require flexible materials that can withstand the mechanical demands of bending, twisting or compression, provide comfort and most importantly withstand repeated washing cycles.*

In this document, we briefly overview the flexible sensors manufactured via different printing approaches and the flexible materials developed by recent studies in this area. Moreover, we discuss a hot topic in current research: self-powered flexible sensors. These sensors eliminate the need for an external power source, enabling fully portability and lightweight wearable devices. On the other hand, we present some challenges encountered in the field of flexible printed sensors.

Key words: *sensorised textiles, wearables, printing, flexibility, comfort, durability*

1. INTRODUCTION

Active smart textiles are fabrics with incorporated electronic components such as sensors, actuators and batteries that can provide added value to the wearer. Apart from conventional fabrics, they can monitor, transform, communicate, or generating/storing energy, giving wearer remarkable benefits that can enhance efficiency and provide a more comfortable and health-focused experience. The growth in the wearable electronics industry, the miniaturization of electronics and developments across flexible electronics are some of the key factors driving the growth of the smart fabric market [1].

Flexible sensors are going to be in tremendous demand owing to their significant potential for wearable electronics and Internet of Things (IoT) applications. Flexible sensors are extensively required in health diagnosis, motion monitorin and human-computer interaction. The healthcare industry is a big user of flexible sensors, ranging from glucose and pH sensors to pressure and strain sensors, and other devices such as wearable patches [2]. The term "flexible sensor" refers to a sensor constructed of flexible materials or structures that can be bent, stretched or folded freely during use and still maintain their electrical and mechanical properties. They are preferred over rigid sensors because the rigid ones often lose their sensitivity when subject to bending. Moreover, they could allow miniaturization of products as they can be packed conformally with the device [3].

Additive manufacturing is a technology that could enable the successful manufacture and expansion of the flexible sensors market. Moreover, by combining textile materials and the various printing technologies, new possibilities could be opened in this sector. Printing technology offers unparalleled flexibility and simplicity in the fabrication of highly complex objects [4] and textiles also, could be the next-generation sensing platform because of their many advantages, like good breathability, softness, and structural elasticity [5].

According to Allied Market Research the global market for printed and flexible sensors is projected to reach $8.6 billion by 2031, growing at a compound annual growth rate (CAGR) of 8.3% from 2022 to 2031. Yet, it is worth mentioning that some important drawbacks in this market are the high manufacturing cost, the increased price of the materials and end-use products and the early stage of manufacturing technologies [2].

2. FUNCTIONAL SENSING MATERIALS FOR FLEXIBLE SENSORS

Important ways that could permit the obtaining of flexible sensors with improved performances are the developing of new functional materials and building special device structures [6].

Is expected that flexible and wearable sensors to provide an accurate and reliable sensing function, and also ensure that the natural movements and comfort of the users are enabled. Therefore, their skin-like conformability and stretchability represent very important characteristics that define these sensors [7]. To achieve these properties, different kinds of materials can be used. There are two basic components, the flexible substrates and the most important, the active sensing element (Figure 1). Research on flexible sensors mainly focuses on enhancing the flexibility and conductivity of the materials utilised in their structure, with electrical conductivity being one of the main properties that makes sensing materials work.

Different printing technologies require different materials to print. Three main types of flexible materials are used in the additive manufacturing area and available on the mass market with different print quality: thermoplastic polyurethane (TPU) materials, CLIP resins (continuous liquid interface production) and silicone rubbers. Among them, TPU is being the most popular material for 3D printing applications, because of its range of benefits, including flexibility, durability, ease of processing, abrasion/scratch resistance, resistance to ultraviolet light and low cost [8].

Other important and long studied and applied materials in the field of printed sensors are also conductive inks. In fact, conductive ink is the core of printing technology and also one of the fastest growing sectors among all ink industries. Metal nanoparticle ink formulations or low-cost inks composed only of graphite flakes and silicone were applied in the field of printed sensors. Graphene-based inks are especially recognized as very promising for future fabrication of devices because of their low cost, unique properties, and compatibility with various platforms such as plastics, textiles, and paper [9].

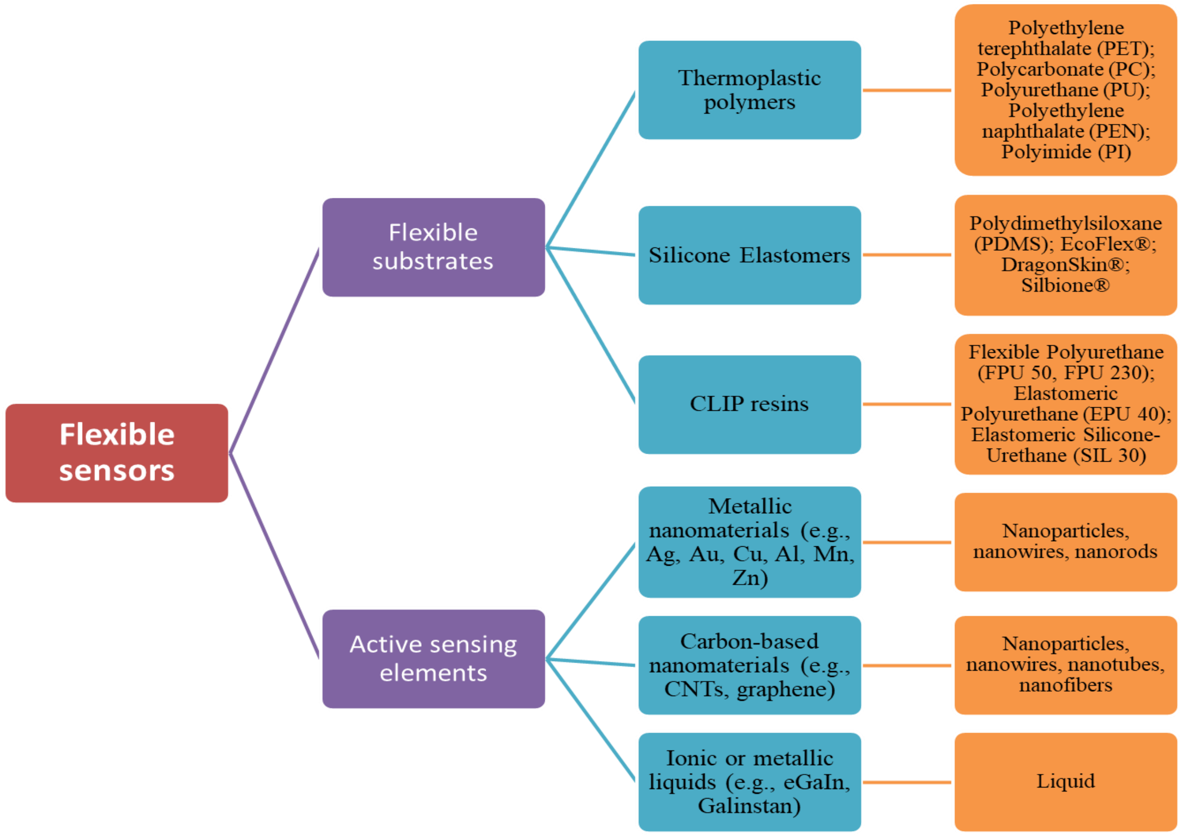

Fig. 1: Basic materials for making flexible sensors

The sensing materials can be divided into the following groups: photo-responsive materials, mechanical-responsive materials, chemo-responsive materials, thermo-responsive materials and humidity-responsive materials based on the response properties of the flexible sensing materials to different stimuli [7].

The selection of materials to be used in printing technology directly affects the characteristics of the object to be printed, namely durability, mechanical properties, and applications [10].

3. FABRICATION TECHNIQUES FOR FLEXIBLE PRINTED SENSORS

Combining textile materials and printing technologies could lead to an impressive development potential for the textile industry.

Different technological approaches were followed over the last years for the manufacture of printed flexible textile sensors:

- Print directly on textiles (using inks or conductive polymeric filaments), the most common method that can add new functions to the existing textiles (Table 1).

Depositing conductive polymeric filaments onto a textile substrate represents an easy and low-cost method to create textile sensors, but the adhesion between the printed material and the textile substrate represents a sensible parameter.

Among the most studied printing technologies with specialized inks are screen-printing, ink-jet printing and direct-ink-writing. Furthermore, the typology of the inks, their deposition and circuit design, as well as the complexities posed by their properties of flexibility and elasticity, raise an issue in their use [11]. Also, because of the inherent fabric properties like porousness and roughness of surface, the formation of electrical materials directly on fabric substrates still represents an obstacle to overcome [12]. Additional barriers to the development of printed sensors are the washing resistance and durability over time.

Table 1: Fexible sensors printed directly on textile substrates

Printing Technology	Sensing Mechanism	Printable Materials	Machine Type	Potential Application	Ref.
FDM (fused deposition modeling)	-	Rubber-like TPU with a carbon black filler (PI-ETPU)	Lulzbot Taz PRO	Biopotentials detection (e.g. electrocardiography (ECG), electromyography (EMG))	[10]
FDM	Strain sensing	TPU	Prusa i3 MK3	Measurement of the breath rate	[13]
Direct-ink-writing	Strain, pressure and EMG sensing	Polydimethylsiloxane (PDMS) mixed with graphite flakes	RegenHu 3D Discovery	Home based monitoring of hand function (neurological and musculoskeletal conditions)	[14]
Screen printing	Strain sensing	Polyurethane (PU) mixed with carbon black nanoparticles and PDMS microbeads	-	User-interface device monitoring respiration and arm motion signals in real time	[15]
Modified extruder	Strain and bending sensing	Sheath-core fibre: styrene–ethylene–butylene–styrene (SEBS) shell and a Ga–In–Sn alloy liquid metal core	Anycubic Chiron printer	Wearable devices in soft robotics, environment sensing, and healthcare monitoring	[16]
Direct-ink-writing	Strain, temperature, ECG sensing	SEBS with carbon black (CB) or Ag flakes and SEBS/PEDOT/CB	RegenHu 3D Discovery printer	Monitoring markers such as physiological temperature, strain, and ECGs	[17]

- Print different textile structures with intelligent functions by using flexible conductive materials.

Due to their flexibility and wearability potential, fibre-shaped materials have received considerable attention in the development of flexible sensors (Table 2).

The most important characteristic of fiber-based sensors is their ability to avoid film-based structure sensors' catastrophic collapse or wrinkling during stretching. Nanoparticles (NPs) are extensively used to enable conductivity in these fibrous shaped printed structures. However, they pose some major concerns, such as the possibility of clogging the printhead and complicating the process of printing [18] or more importantly, the biocompatibility and the risks associated with human health, especially in the field of printed medical sensors, as they can cross cell membranes [19].

Table 2: Fiber-shaped printed flexible sensors

Printing Technology	Sensing Mechanism	Printable Materials	Machine type	Application	Ref.
FDM	Strain sensing	TPU fibrous textile coated with AG NPs	PMAX 3D printer	Wearable electronic component to monitor human motions and facial expressions	[20]
Extrusion	Capacitive strain sensing	Multicore–shell fiber: silicone elastomer (Dragonskin 10) and ionically conductive fluid	Custom built 3D printer (ABG 10000, Aerotech Inc.)	Wearable electronics, human/machine interfaces, soft exosuits, and soft robotics	[21]
FDM	Strain sensor	Mesh-like structures from conductive polylactic acid (PLA)	Flash Forge Creator Pro 2	Soft and wearable robotics	[22, 23]
Direct-ink-writing	Tactile sensing	Coaxial core-sheath fibre: PDMS and graphene and polytetrafluoroethylene (PTFE) particles	Home-made 3D printer	E-skin	[24]
Extrusion	Strain sensing	MXene-Reinforced Cellulose Nanofibril Inks	JDX01 printer from Changsha Nayi Co., Ltd	Monitoring finger and wrist bending, swallow of the throat and speaking	[25]
FDM	Piezoelectric sensing	Polyvinylidene fluoride (PVDF) matrix with barium titanate NPs and a silver ink	-	Wearble sensor for knee joint and respiration monitoring	[26]

4. SELF-POWERED PRINTED SENSORS

Self-powered sensors have been in great demand recently in wearable applications. Current wearable sensors require additional bulky batteries that need to be often recharged or replaced so the system could function normally. Therefore, self-powered sensors represent a promising alternative in this field. Two types of sensors are included in this category, piezoelectric and triboelectric sensors. Their sensitivity is a change in the output current or voltage under pressure [27].

Printing technology was used in various studies to create such types of sensors. Huang et al. have made a hyper-stretchable self-powered sensor based on nano/microfibers using a helix electrohydrodynamically printing method, which demonstrated ultra-high mechanical stretchability (>300%), ultra-low detection limit (<1 mg), and excellent durability. The printed fibers were obtained from PVDF which were sandwiched between Ecoflex substrates and a PDMS interlayer [28].

Also, Cao et al. fabricated a self-powered touch/gesture tribo-sensor that showed very good performances by using CNTs (carbon nanotubes)/PU ink screen-printed on a nylon fabric and a silk fabric layer serving as frictional material. The sensor exhibited high sensitivity and flexibility, fast response time and excellent performance under harsh mechanical deformation (e.g. washing) with great potential in multi-functionalities wearable devices and human machine interface systems [29]. Screen-printing was also chosen by Islam et al. to fabricate graphene-based conductive pattern on textile substrates that served as a highly conductive, flexible, and machine-washable e-textile platform to store energy and monitor physiological conditions including bio-signals [30].

5. CONCLUSIONS

Printing methods have advanced recently, resulting in time and cost savings, and becoming more easier and environmentally friendly. Various flexible additive manufactured textile-based sensors have been developed, but there is still room for improvement in the process and performance of printed sensors. These sensors need to fulfill many characteristics such as precision, reliability, repeatability, and the resistance to mechanical deformation, so they could be used successfully and determine the widespread of wearable e-textiles.

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