Journal of Engineering Science and Technology Review 18 (1) (2025) 1-10

Review Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Tracking the Progress Development of Stretchable Strain Sensor in Different Applications Based on Clustered Review Studies

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Received 23 March 2024; Accepted 13 October 2024

Abstract

Strain sensors made of metals and semiconductors have stiff limitations, are challenging to install on curved surfaces and are limited in deformation. To overcome these problems, many researchers have developed flexible sensors. This article will discuss the process of making flexible strain sensors with Additive Manufacturing (AM) technology. The performance characteristics of flexible strain sensors will also be studied, including stretchability, sensitivity or gauge factor (GF), response and recovery time, linearity and durability. The results of the review show that 3D Printing Fused Deposition Modeling (FDM) and Direct Ink Writing (DIW) technologies have the advantage of manufacturing complex shapes, producing minimum waste, and being faster than conventional manufacturing. In principle, flexible strain sensors consist of conductive materials and flexible materials. In the process of making flexible strain sensors using FDM technology, sensors are made using flexible conductive filaments, while DIW technology is made using conductive ink. In other words, flexible strain sensors using additive manufacturing are promising to be used in detecting the human body, sports, health monitoring, and soft robotics.

Keywords: Flexible strain sensor, Fused Deposition Modelling, Direct Ink Writing, Conductive filament; Conductive ink.

1. Introduction

The degree of distortion in a structure brought on by applied forces or loads is known as strain. Depending on the type of force being exerted, strain may take the form of tension or compression. The strain sensor is designed from the concept of strain changes required in some applications of sensors. The strain sensor works by transducing external mechanical stimuli into electrical signals. In the past, strain sensors were used to detect building damage by measuring deformation, which is made of metal and semiconductors. These materials were stiff and difficult to install on curved surfaces and could not detect large deformation changes [1]. To overcome the limitations of metal- or semiconductor-based strain gauges, many researchers have studied flexible sensors that can be attached to human skin [2]. The basic principle of a flexible strain sensor generally consists of three components: a transduction electrode, a functional composite structure, and a connecting cable [3].

Currently, the use of flexible stretch sensors has developed rapidly, such as in the field of soft robotics [4], detection of human movement [5], Biomedical [6], and wearable (bio)sensor [7]. In addition, a more specific application related to the use of sensor strains was carried out by Kantarak et al. in the application of Parkinson's tremor patients. The strain sensor was designed to determine the number of hand vibrations that occur in real-time [8]. The performance of a flexible strain sensor can be seen from several performance parameters such as stretchability, sensitivity, hysteresis, response and recovery time, overshoot behavior, linearity, durability, and others [9]. The parameters of a flexible strain sensor are influenced by four main factors: the type of conductive material used, the flexible material, the manufacturing process, and the type of solvent used.

Conductive materials used to make flexible strain sensors generally use carbon nanotubes (CNT) [10], [11], graphene [12], carbon nanofiber [13], gold [14-16], carbon black (CB) [17], [18], and AgNps [19-21]. The purpose of using conductive materials is to increase the sensitivity of the strain sensor. However, flexible materials are also required to increase the flexibility of the strain sensor. Some of the flexible materials applied in strain sensors were thermoplastic polyurethane (TPU) [22-24], Polydimethylsiloxane (PDMS) [1], [25], [26], ecoflex [1], Silicone rubber [27], polypyrrole [21], and polyurethane sponge (PUS) [28]. In addition, the use of solvents also affects the optimization of flexible strain sensor manufacturing. The solvent aims to disperse the conductive material so that it spreads evenly. Some of the solvents used by previous studies were 1-Methyl-2pyrrolidone [1], n-Hexane [1], (DI) water [1], [29], 2-Propanol [1], Toluene [1], [25], Chloroform [1], Isopropanol [1], ethanol [17], [30], and chloroform [31].

Besides materials, the manufacturing process largely determines the final performance of a flexible strain sensor. Several studies on flexible strain sensors used methods such as casting[1], spray deposition [5], Fused Deposit Modeling (FDM) 3d print [32], [33], direct ink writing (DIW) 3d print [34], [35], and electrospinning [24]. The first is the sandwich casting method performed by Dong-Hyun et al. by mixing 0.03 g of multi-walled carbon nanotubes (MWCNT) with 15 ml of solvent, and then the mixture was ultrasonically dispersed. After that, the stirring process was carried out for 10 minutes at 300 rpm. The mixed CNT and solvent were poured into an I-shaped mold and then coated with a PDMS

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ISSN: 1791-2377
doi:10.25103/jestr.181.01

or Ecoflex substrate [1]. Investigation using the sandwich method was also carried out by Chen et al. This study used graphene nanoplate conductive material and PDMS flexible material and layered into three different layers [30].

Del Bosque et al. mixed the graphene nanoplate (GNP) and Ecoflex conductive materials manually, followed by a rolling process with the aim that the GNP material could be perfectly dispersed. The next process is degassing, which aims to remove gas from the GNP and Ecoflex mixture after it is printed[7]. Liu et al. mixed CNT conductive material and PDMS flexible material. Liu et al added that the laser process uses CO_2 to increase the superhydrophobicity of the developed flexible strain sensor [25]. The manufacture of flexible strain sensors with a mixing process was also carried out by Cristiane et al., namely with the conductive material Graphite and flexible biodegradable polymer (PBAT) [31]. A different manufacturing process was carried out by Zhan et al., namely by using electrospinning technology to print flexible material from TPU material, then the TPU mat was coated with PDA solution to make the surface of the TPU rough. After that, it was coated using CNT material and AgNPs [24]. In recent years, additive manufacturing methods have been used to make flexible strain sensors [36], [37]. Additive manufacturing technology is considered to be the key technology for changing traditional manufacturing processes into modern or intelligent manufacturing processes that aim to produce a product. The precision, accuracy, and ability to print things in accordance with our designs are all capabilities of this technology [38]. The main benefits of 3D Printing are freedom of design, minimization of waste, mass customization, and the ability to produce complex structures and rapid prototyping [39]. Research on flexible strain sensors with additive manufacturing fabrication methods has been widely studied. The AM technology used is material extrusion, namely Fused Deposition Modelling (FDM) [40] and Direct Ink Writing (DIW) [41].

In terms of performance, this review article will outline the additive printing process used to make flexible strain sensors, including stretchability, response and recovery time, sensitivity, linearity and durability (Figure 1). In addition, this paper also presents novel recommendations to improve the performance of the flexible strain sensor that will be made. This review article will also map related applications of flexible strain sensors.

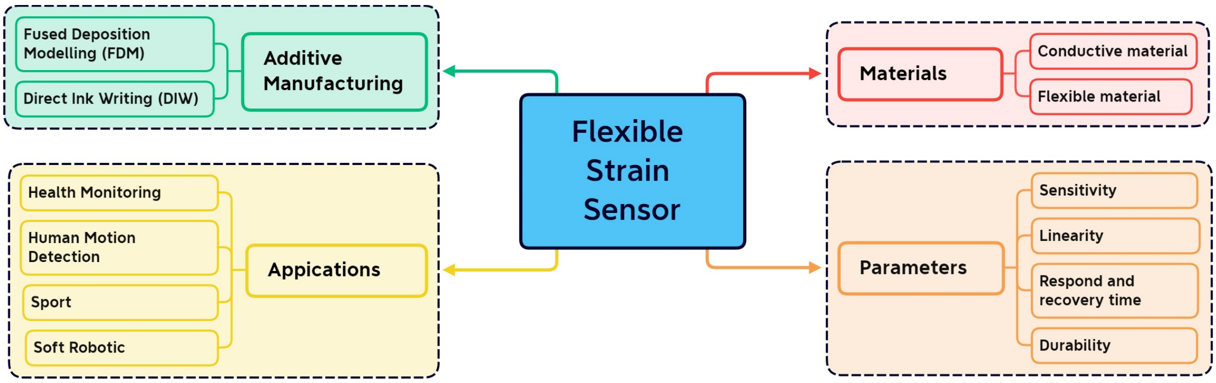

Fig. 1. The flexible strain sensors schematic fields.

2. Additive manufacturing technology

Additive Manufacturing (AM), also referred to as 3D printing, is a novel technique that has drawn interest from both business and academics recently [42], [43]. This is a new technology with the principle of combining materials layer by layer to create a three-dimensional product based on the files we have designed. AM technology is considered to be the key technology to transform traditional manufacturing processes into modern or intelligent manufacturing processes that aim to produce complex products [44]. This technology can produce parts from micro to macro scale, precision, and accuracy of parts, and can be printed according to the designs we have made [45], [46].

According to American Society for Testing and Materials (ASTM) guidelines, the six stages of the additive manufacturing process include material extrusion, directed energy deposition, powder bed fusion, vat photopolymerization, sheet lamination, and material jetting [47]. One method of material extrusion is 3D printing. It could be divided into three categories: liquid, powder, and solid, depending on the different types of input materials. There were some discussions reported about 3D printing. Muflikhun et al. [48] conducted a research about 3D printing of carabiner with different orientation. In this research, the characteristics of the filament deposition process and component performance after printing were observed. Remodeling of the carabiner was also carried out using different design parameters. Polylactic Acid (PLA) is used as a 3D printing material. The printing orientation and filler density were varied in this investigation. The test results showed that the deposition process was very important in the 3D process. The greatest strength was obtained in the X orientation (parallel to the force applied to the model) with 100% infill. In specimens of this orientation, the failure mode occurred at the edges of the specimen, where the highest loads occured. If viewed from PLA consumption, 93% efficiency was achieved by X orientation at a filling density of 20%.

Some research on additive manufacturing is presented in this paper. The use of FDM method was also investigated by Muflikhun et al. [49]In this study, there were 3 materials compared, which were PLA materials from FDM process only, liquid crystal display (LCD) only, and combination of both, called hybrid materials (HM). Best achieved are the tensile and flexural strengths by FDM samples. Likewise with hardness and density, the highest values were obtained for the FDM sample. However, the hardness value of the HM sample almost matches that of the FDM sample. There is a significant difference in surface roughness values for the FDM and HM samples between the longitudinal and axial directions. This research also reports that the performance of products resulting from a combination of FDM and LCD processes depends on the type of material that composes them, and this process combination has the potential to be used in reinforced material applications. In addition, integrated deposition modelling was used by Nugraha et al. [50] to produce a figure-eight-shaped model made of polylactic acid (PLA).

This model was then reinforced with glass fibre reinforced polymer (GFRP). Tensile, hardness, surface roughness, and density tests were conducted to determine the properties of the composite. The findings showed that the laminated composite could increase the tensile strength by a factor of more than two, with the maximum strength measured at 4977.3 N. The highest hardness and density values that could be achieved were 75.1 Shore D and 1.2 g/mm, respectively.

The production of flexible strain sensors using several extrusion material types will be covered in this review. One of the methods used in additive manufacturing (AM) is called material extrusion. Constant pressure is used to force the material through a nozzle. After leaving the nozzle, the extruded material will be put on the substrate steadily and hardened there. For solid pieces to form and stay in the structure throughout the process, the new material must also adhere to the old material. Some of the methods that use extruded materials include Direct Ink Writing (DIW) and Fused Deposition Modeling (FDM) 3D printing as seen in Figure 2. In Figure 2a, researchers must create or use conductive ink which is then prepared in a nozzle and printed using DIW 3D printing [51], [52]. Meanwhile, for FDM 3D printing, researchers must create or use conductive filaments [53], [54] (Figure 2b).

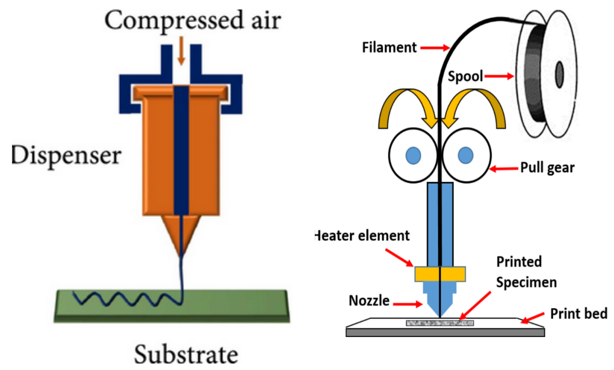

Fig. 2. Illustration of extrusion material, (a) DIW [55] dan (b) FDM [56].

2.1. Direct Ink Writing (DIW) 3D Print

3D Printing type DIW is a printing method in which liquid suspension, in this case, conductive ink, is extruded using pressure through a needle by piling up layer by layer into a sensor material controlled by a computer (Figure 3). This process is straightforward and flexible enough to use many materials, including monolithic and composite ceramics, polymers, metals, and food products [57]. This method has many advantages over other methods and can realize multi-material Printing [58].

The first step in making strain sensors with the DIW method is that researchers must make conductive ink. In general, conductive inks are made with several stages of the process such as mixing conductive materials such as CNT, Graphene, CB, and AgNp with solvents such as IPA, DI water, and ethanol using a magnetic stirrer. After that, the conductive liquid is mixed with flexible materials such as PDMS, Ecoflex, and Silicone rubber. The second process is preparation into a nozzle, this nozzle is usually connected to an extrusion system that can control the ink flow with precision. The third stage is ink extrusion, the ink is pushed through the nozzle using pressure (either air or mechanical pressure). This process requires very precise control so that the shape and dimensions of the mold match the desired design, hence the need for CAD (Computer-Aided Design) to extrude the ink in thin layers. The final step is drying to form a solid structure. This drying process can occur naturally at room temperature or can be accelerated using heaters or UV light, depending on the type of ink used [59], [60]. Referring to the research developed by Zhao et al [61], they created strain sensors using the DIW method to monitor load and detect damage in composite materials (Figure 3a).

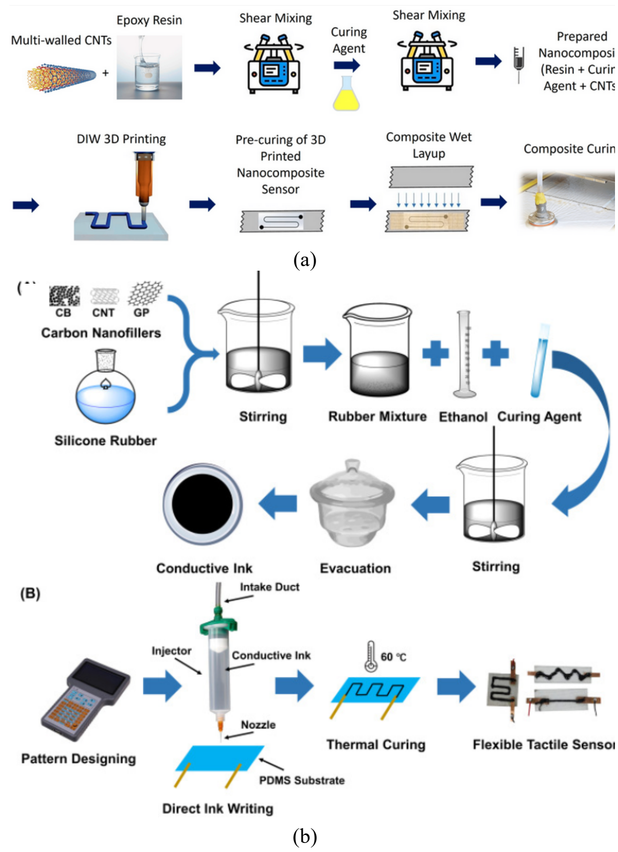

Fig. 3. DIW 3D printing principle and printing equipment. (a) Fabrication processes strain sensor[61], (b) The synthesis of conductive inks and Manufacturing of flexible strain sensors using AM (Adapted from [17]with permission from Elsevier).

As with most other additive technologies, an important part of DIW technology is the configuration of the conductive liquid as the material for which the sensor is made. The conductive liquid must be homogeneous (dispersion), and bubbles must be removed to get a good sensor [62]. Conductive ink requires low viscosity, good viscoelasticity, and low-pressure flow through the nozzle. In DIW technology, nozzle size significantly impacts the printing outcome. To maximize print resolution, a smaller diameter nozzle is often used; however, the smaller the diameter, the greater the extrusion pressure and the longer the molding time. The pressure must be selected by the size of the nozzle of the printed material to guarantee the smoothness and resolution of the Print.

Ma et al. [17] have made a flexible strain sensor using the 3D Print DIW method using conductive materials CB, CNTs, and graphene and mixed with flexible RTV material. The study's findings demonstrate that the ability to print conductive routes with a regulated shape and high conductivity depends critically on rheological characteristics and printing speed. Chen et al. [35] also made a flexible strain sensor using the 3D Print DIW method using CNT material. The study's findings demonstrated that the sensor exhibited good stability during 900 repeated stretches under 20% pressure and a high strain with a sensitivity of 18.55 at a tensile strain of 20%.

2.2. Fused Deposition Modeling (FDM) 3D Print

Several researchers have recently carried out the manufacturing process for flexible strain sensors using 3D Printing. The 3D print process is considered capable of being made according to the taste of researchers without having to make prints first. Xiang et al. [63] researched flexible strain sensors with FDM Technology manufacturing. The main material used is CNT/TPU (carbon nanotube/thermoplastic polyurethane). The results of the study by Xiang et al. show that the flexible strain sensor has a GF value of 117213 at 250% strain. Besides that, the sensor also has a good stability value of 1000 cycles. In 2020, Xiang et al. [64] developed their research on flexible strain sensors using the FDM Technology method using CNT/AgNP/TPU/DMF material, GF = 43260 at 250% strain, great linearity (R = 0.97 at 50% strain, quick response 57 ms, and excellent repeatability (1000 cycles).

In general, flexible strain sensors produced using Fused Deposition Modeling (FDM) 3D printing require the use of conductive filaments. These filaments must exhibit both flexibility and conductivity. Typically, conductive filaments are made from a mixture of conductive materials such as carbon black (CB), graphene, or carbon nanotubes (CNT) combined with a flexible polymer like thermoplastic polyurethane (TPU) [33], [65]. The resulting mixture is then fed into an extruder to produce the conductive filament. This filament is subsequently loaded into the FDM 3D printer, where it is used to print the flexible strain sensor. Figure 4 shows the flexible strain sensor manufacturing process using FDM technology. In principle, extruder machine technology is needed to make conductive filaments to manufacture flexible strain sensors using the FDM Technology method.

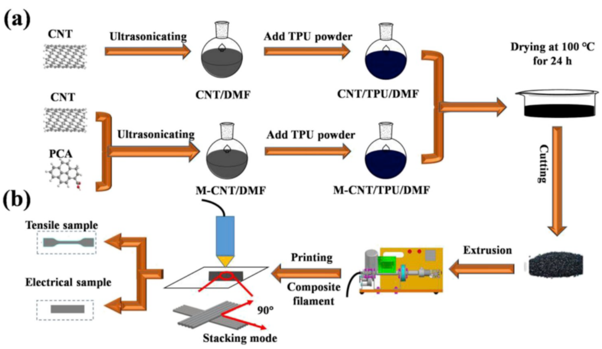

Fig. 4. (a) Mixing of conductive material and flexible material; (b) fabrication of filament and sensor (Adapted from [66] with permission from Elsevier).

The FDM method for manufacturing flexible strain sensors is also used by Sezer and Eren [32] with MWCNT and ABS materials granules. According to the study's findings, adding 7% by weight of MWCNT to ABS significantly enhanced the tensile strength (up to 58 MPa, or 288% strain). Hia et al. used a different type of flexible material to make the sensor, and they combined poly(ethylene-co-methacrylic acid) (EMAA) with MWCNT [67]. The sensors can produce an electrical conductivity of 43.9 S m^{-1}. Li et al. [68] also researched flexible strain sensors with FDM technology using Mxene/MnFe2O4/MWCNTs material reinforced with TPU. The sensor is durable (cyclic compression 6000 seconds), with a compression range of GF = 1.33-3.73 and an 89% strain at 12.03 Mpa pressure. The sensor's intended use is to track human movements, such as finger and wrist flexion and voice recognition.

3. Composite Materials

This section discusses the materials used in the manufacture of flexible strain or pressure sensors. The materials are categorized into substrate materials and active materials, depending on their function in the flexible sensor. The substrate serves to provide the support or framework in which the active material is placed to perform sensing [69], [70]. Xiang, et al [63] illustrated the working system of the strain sensor before and after being stretched as shown in Figure 5. Figures 5a and e show that controlling the interweaving between CNTs is quite difficult. However, the synergistic effect between AgNPs and CNTs further improves the quality of the conductive network in the polymer matrix, as shown in Figures 5b and f. With an increase in the amount of AgNO3, the AgNPs will agglomerate and grow larger, resulting in a more foldable and less dense conductive network within the elastomer matrix, as shown in Figures 5c and g. The high resistivity of the AgNP/TPU composites can be mainly attributed to the significant agglomeration of AgNPs during the reaction process, which reduces the dispersion of AgNPs in the TPU shown in Figure 5d and h.

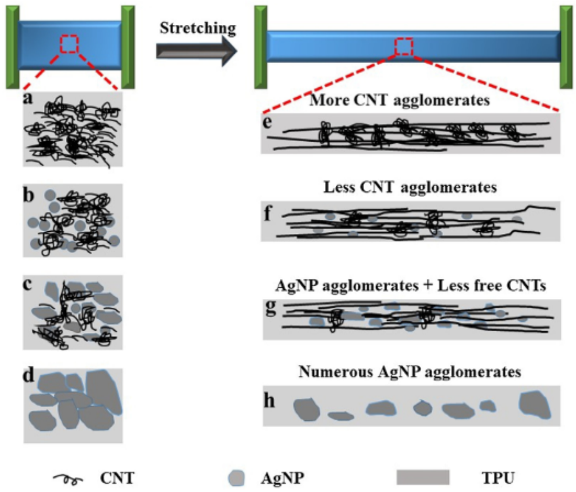

Fig. 5. Illustration of how a flexible strain sensor works (Adapted from [22] with permission from Elsevier).

3.1. Flexible substrates

Polymers are often chosen as substrates in the manufacture of flexible strain sensors due to their affordability, good compatibility, biocompatibility and flexibility. Sensors designed to be worn on human skin must be able to function without causing side effects. In addition, the uneven shape of human skin limits the use of rigid materials. Therefore, the materials used for wearable sensors must have a sufficient degree of flexibility and stretchability to follow the contours of human skin. The most commonly used polymers as substrates include PDMS, Ecoflex, PET and TPU. Among these polymers, PDMS is the most widely used for flexible sensors due to its various advantages, such as chemical resistance, low cost, optical transparency, customizable mechanical properties, biocompatibility, and ease of processing [71], [72]. Figure 6 shows an illustration of the materials that make up the flexible strain sensor.

In research conducted by Zhou, et al [73], it is explained that flexible strain sensors with PDMS substrate materials and carbon conductive materials have great potential in various applications, ranging from motion detection to wearable electronics. This sensor shows a GF of 3026.9 and high durability (>5000 cycles). In addition, Xu, et al [74] also developed strain sensors with PDMS substrate material for health monitoring and motion tracking applications. The sensor showed quick response speed (~80 ms), high sensitivity (above 4000) and good stability (above 6000 cycles).

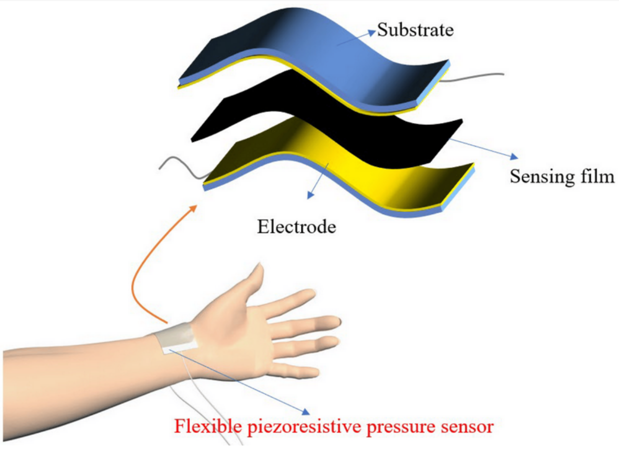

Fig. 6. Illustration of the materials that make up the flexible strain sensor[75].

3.2. Active materials

The active material is the most critical component in flexible strain sensors due to its role in converting mechanical stimuli into resistance signals [76]. The main requirement of the active material is to have good electrical conductivity and abundant conductive pathways, ensuring that the sensor can respond to small strain changes and remain functional even when subjected to large strains [77]. Some conductive materials that are often used to make strain sensors are carbon nanotubes (CNT), carbon nanofiber, carbon black (CB), graphene, gold, and AgNPs. Based on the grouping conducted by Hia, et al [78] CNT material has the highest conductivity compared to other conductive materials as shown in Figure 7.

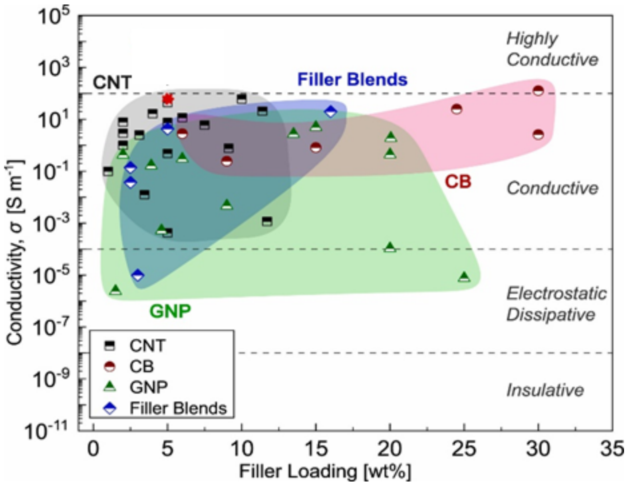

Fig. 7. Characteristic maps for electrical conductivity (mass fraction) [78].

In research conducted by Sun et al. [79] made a flexible strain sensor using the DIW Technology method using conductive carbon nanotube materials as well as flexible polyaniline materials and flexible gelatin NH3, and their research results show that the sensor can withstand toughness for 2000 cycles with 5% strain. Additionally, Zhao et al. [51] studied flexible strain sensors by utilizing flexible polydimethylsiloxane (PDMS) and conductive silver-coated-glass fiber (AGF) and carbon fiber (CF) materials to create conductive silicon rubber. The findings indicated that the sensors had GF values of 8–10 at various strain rates.

4. Evaluation of performance parameters

Electromechanical characterization is usually performed to assess the performance parameters of flexible and elastic strain sensors using various composite materials and structures. All parameters including sensitivity, linearity, response and recovery time, and robustness tests on flexible strain sensors using FDM and DIW methods; are discussed in this section based on the reviewed literature. Table 1 summarizes the performance parameters of the elastic strain sensors of the various composite grades reviewed.

Table 1. Summary of functional test of the flexible strain sensor

No	Material	Manufacturing	Sensitivity (strain)	Linearity (strain)	Response and Recovery time	Durability (strain)	Ref.
1	TPU/CNTs/AgNPs	FDM	43260 (250%)	0.97 (50%)	~57 ms	1000 Cycle (10%)	[22]
2	CNT/Fiber PDMS	DIW	7.23	0,997 (50%)		4500 s	[41]
3	CB/GP/silicone rubber/PDMS	DIW	1918.4 (20%)			7000 s	[17]
4	MXene/$MnFe_2O_4$/MWCNTs reinforced TPU	FDM	3.73 (~89%)			6000 s (60%)	[68]
5	TPU/CNTs	FDM	2.661 (0~3%)		130 ms(response) 250 -ms(recovery)	3000 s (5%)	[80]
6	CNT/TPU	FDM	117213 (250%)			1000 cycles (10%)	[63]
7	CBPs/TPU	FDM	2.653 (0~3%)		120 ms	> 3000 cycles	[66]
8	Graphene/ Carbon Nanotube Aerogel	DIW	18.55 (20%)			900 s (20%)	[35]
9	carbon-nanotube-reinforced polylactic acid (PLA-CNT)	FDM	1342.1 (0.5%)			2300 cycles (2%)	[81]
10	Ca-PAA-SA-CNTs Hydrogels	DIW	6.29 (50%)				[82]
11	κ-carrageenan/PAAm DN hydrogel	DIW	0.63 (1000%)				[83]
12	TPU/CNTs–ILs	FDM	440 (50%)				[84]
13	CNT/GNP(3:1)/TPU	FDM	136327.4 (250%)	0.97 (30%)		3000 cycles (5%)	[85]

No	Material	Manufacturing	Sensitivity (strain)	Linearity (strain)	Response and Recovery time	Durability (strain)	Ref.
14	multi-walled carbon nanotube (MWNT)/polydimethylsiloxane (PDMS)	DIW	12.15 (70%)			8000 (10%)	[86]

4.1. Sensitivity
Sensitivity can be defined as the response of the sensor's output to a variation in one unit's input. The sensitivity of the strain sensor can be determined using the Gauge Factor (GF), which is defined as the ratio of the change in resistance to the applied strain [87], [88].The following equation can calculate GF:

$$GF = \frac{\Delta R}{R\varepsilon} \tag{1}$$

where R is the initial resistance of the sensor, ΔR is the change in resistance that occurs in the sensor when stretched, and ε is the strain. The higher the GF value, the more sensitive the flexible strain sensor.

Xiang et al. [22] researched making flexible strain sensors with TPU/CNTs/AgNPs materials and a manufacturing process of FDM Technology. This research resulted in a high GF value of 43260 at 250% strain. Ma et al. [17] also conducted the same research with the FDM Technology manufacturing process using CB/GP/silicone rubber/PDMS material, resulting in a GF value of 1918.4 with 20% strain.

4.2. Linearity
Another key desirable feature of a sensor is linearity. The linearity parameter for flexible sensors specifies that the sensor's input and output should be linearly related for straightforward data processing. Non-linearity is determined to estimate the sensor output deviation from a given calibration curve. The coefficient of determination (R^2) was computed using linear regression. If the R^2 value is high, the sensor's performance is considered linear. Generally speaking, achieving adequate sensitivity over a large linearity range is challenging[89].

Yan et al. [41] employ DIW 3D Printing technology to create flexible strain sensors. The sensor's sensitivity rose by 18.23 (a 2.52-fold increase) and maintained a linear response of 0.997 in the study using CNT/Fiber PDMS material. Xiang et al. [22] researched making flexible strain sensors with TPU/CNTs/AgNPs materials and an FDM Technology manufacturing process. This research yielded a linearity value of 0.97.

4.3. Response and Recovery time
Another critical consideration is the transient responsiveness of high-performance strain sensors, which is impacted by response and recovery lengths. To test the sensor's stability at the applied strain, the prescribed strain is typically applied with a high-speed data gathering system and held for a while. Next, the applied strain is released, and the recovery signal is monitored. Del Bosque et al. researched flexible strain sensors with the main material graphene nanoplatelet (GNP)/Ecoflex with a molding manufacturing process. To disperse conductive materials, Del Bosque et al. used the three-roll milling (3RM) method with a different speed ratio of 1:3:9. The results showed that the response time and recovery time of the flexible strain sensor were 220 ms and 978 ms [6]. The same study was also carried out by Li et al. with the main material CNT/TPU, where the response time and recovery time were faster, namely 130 ms and 250 ms [65].

4.4. Durability
Durability is a crucial factor for evaluating how well flexible sensors operate over prolonged use. The sensing layer and substrate material are currently the only flexible components of flexible sensor systems. However, other parts are constructed of stiff materials, such as cable joints and energy storage units. The sensor coating of wearable, flexible sensors may become damaged or come off over time due to a variety of circumstances, such as bending, stretching, and twisting. It might endure mechanical wear and tear, sweaty skin conditions, various weather conditions, and other causes throughout its use. Additionally, after a prolonged loading and unloading cycle, it's possible that the sensor won't work properly. As a result, flexible sensors can achieve excellent durability.

The results of research conducted by Joo et al. with the composition of the CNT/Ecoflex material show that the strain sensor has excellent resistance performance. The sensor can operate up to close to 3000 s with repeated stretching and not being stretched[1]. Research using the DIW Technology method was also carried out by Yan et al. with a CNT/Fiber PDMS material composition showing that a strain sensor can work within 4500 s [41]. Li et al.[68] also made a strain sensor with good resistance, which can last for 6000 s in a pull-and-release test with a strain of 60%.

5. Applications

Flexible strain sensors are implemented in various application fields such as human health care, human motion detection (finger, wrist, knee), sports performance monitoring, as well as soft robotics. The application will be reviewed in this review paper in accordance with the latest literature. Stretchable strain sensors can be used to monitor the movement of the human body. Wang et al. used a flexible strain sensor for human swallowing motion detection applications. The frequency of ΔR/R0 increases during the fast swallowing process [26]. Another application of the flexible strain sensor is to detect changes in the mouth opening and closing. The ΔR/R0 value will increase as the model in the photo opens its mouth [90]. In addition, the application of a flexible strain sensor is for the detection needs of human finger movements [26]. The greater the strain value of the flexible strain sensor, the greater the ΔR/R0 value. This happens because the distance between the conductive particles is getting further away. Research on the application of flexible strain sensors was also carried out by Zhao et al. [88] to detect movements in the wrist, knee joints, human fingers, and Chen et al. [91] in elbows.

Yang et al. [92] also made a flexible strain sensor for application in the sports field to track hand movements at three different frequencies and monitor hand position during badminton practice. Another application in the health sector is to determine the number of human respirations and monitor the pulse of the wrist [31]. In addition, Kantarak et al. also made a glove-based flexible strain sensor to detect the number of tremors in patients with Parkinson's tremors. These gloves use the Arduino nano microcontroller, and then the data is displayed on a computer/handphone [8]. Real-time detection for the soft robotic gripper was also carried out by Qu et al. The grippers are driven by a two-finger pneumatic system and a sensing frame, which can grasp objects with different fingers and reflect the gripping state [93]. Figure 8 shows the application of the flexible strain sensor.

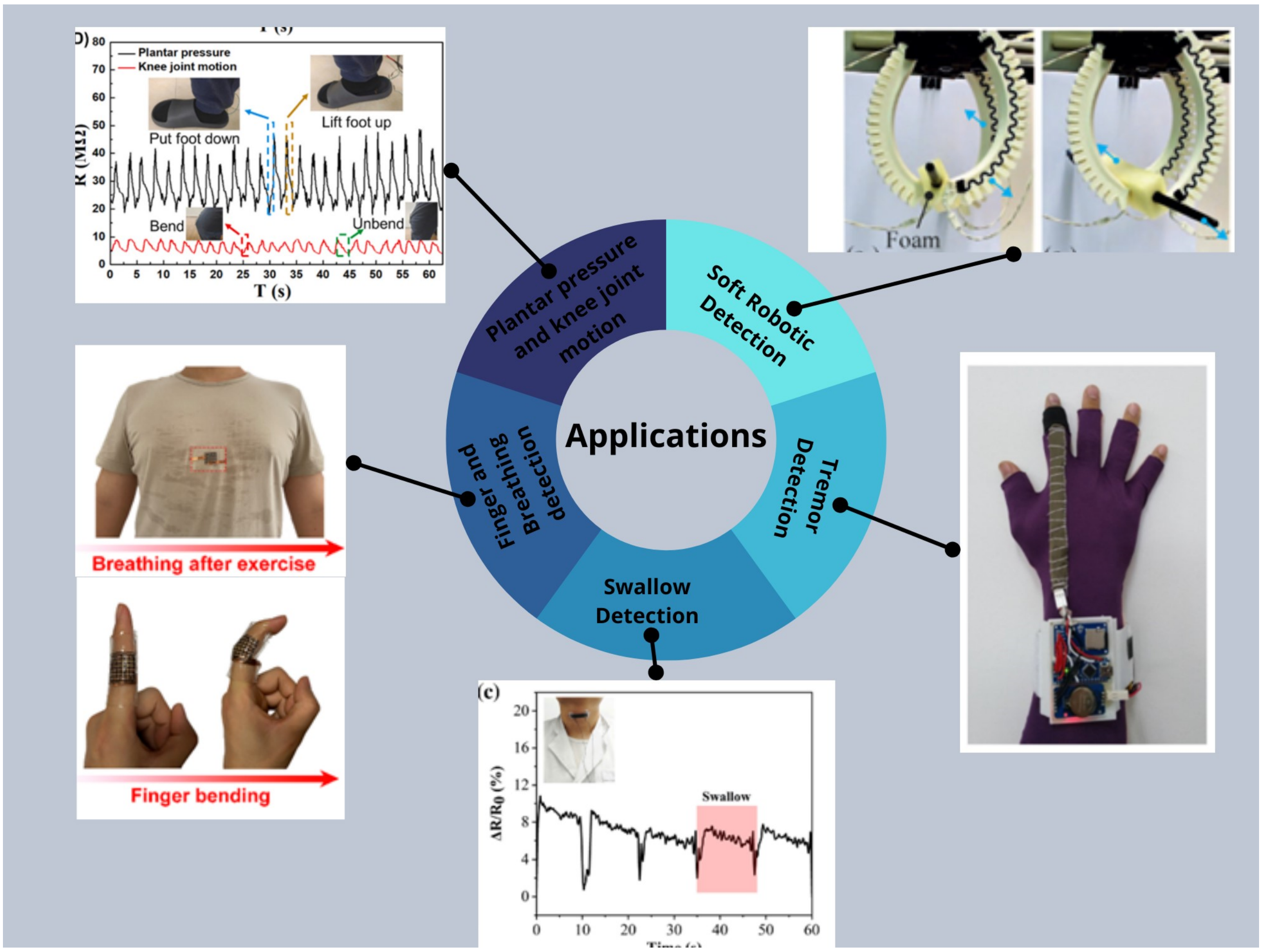

Fig. 8. Applications of flexible strain sensors; Plantar pressure and knee joint motion (Adapted from [17] with permission from Elsevier), Soft robotic detection (Adapted from[94]), Tremor detection (Adapted from[8], with permission from Springer Nature), Swallow detection (Adapted from[53], with permission from Springer Nature), and Finger and Breathing detection (Adapted fro[82], with permission from ACS Publications).

6. Conclusion

This work reviews all the recent trends in the development of flexible and stretchable strain sensors from the perspective of fabrication methods using additive manufacturing technology for wearable applications. The additive manufacturing process that researchers often use to make flexible strain sensors is a type of extrusion material. The results of the review show that 3D Printing Fused Deposition Modeling (FDM) and Direct Ink Writing (DIW) technologies have the advantages of design freedom, mass customization, waste minimization, and the ability to produce complex structures, as well as rapid prototyping. Flexible strain sensors generally use two types of guide materials: flexible and conductive. The types of flexible materials commonly used to make strain sensors are thermoplastic polyurethane (TPU), polydimethylsiloxane (PDMS), ecoflex, polypyrrole, and polyurethane sponge (PUS). The conductive materials used to make strain sensors are carbon nanotubes (CNT), carbon nanofiber, carbon black (CB), graphene, gold, and AgNPs. The fundamental difference is the flexible strain sensor manufacturing process. In FDM Technology, researchers have to make a filament by mixing flexible and conductive materials, which are then inserted into the extruder machine. Meanwhile, in DIW Technology, a combination of flexible materials and conductive materials must be mixed into conductive ink, which can then be printed onto a 3D Print workbench.

In general, both DIW and FDM methods of manufacturing flexible strain sensors have their advantages and disadvantages. One of the advantages of 3D printing with DIW is the better adhesion strength between layers compared to FDM. In general, material properties can decrease due to stress concentration formed in pores or voids [98][99]. However, DIW also has disadvantages such as a more complex process and higher cost than FDM. Both methods, DIW and FDM, excel in producing complex shapes, produce minimal waste, and have faster processes than conventional manufacturing methods. In addition, it can be concluded that the manufacture of flexible strain sensors using the additive manufacturing method can be applied to the detection of the human body, sports, health monitoring, and soft robotics.

The technological challenges and future trends in the manufacture of flexible strain sensors can use additive manufacturing technology. Researchers can develop dual nozzle 3D printing technology. Where currently the process of making a flexible substrate as a flexible material has been made separately. Researchers only attach the flexible substrate to the 3D Print table, then the sensor material is printed according to the needs of the researcher. In addition, the drying process is also carried out separately using a thermal curing tool. This problem can be solved by making dual nozzles, where the first nozzle functions to remove the flexible substrate while the second nozzle removes the sensor material. The drying process can also be done on a 3D printing machine by adding ultraviolet (UV) light that moves in the same direction as the nozzles.

Acknowledgment
Financial support provided by the Center for Higher Education Funding (BPPT) and Indonesia Endowment Fund for Education (LPDP) on decree no. 02144/J5.2.3./BPI.06/9/2022 is greatly appreciated.

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