Biointerface Research in Applied Chemistry
Platinum Open Access Journal (ISSN: 2069-5837)

Review
Volume 12, Issue 3, 2022, 3513 - 3521
https://doi.org/10.33263/BRIAC123.35133521

Sensor-Based Additive Manufacturing Technologies

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Received: 3.06.2021; Revised: 18.07.2021; Accepted: 22.07.2021; Published: 9.08.2021

Abstract: Additive manufacturing is the term that uses the CAD data to build components layer by layer; it is also termed layered manufacturing or 3D printing. The major advantage of additive manufacturing is the capability of building components without the use of molds or tools. Five major categories of AM processes include Powder Bed Fusion (PBF), Direct Energy Deposition (DED), Material Jetting (MJ), Binder Jetting (BJ), and Sheet Lamination (SL). The sensor may be defined as a device that responds to a physical stimulus and transmits a resulting impulse. Sensor technology has been widely adopted in advanced manufacturing, aerospace, biomedical and robotic applications. Commonly used sensors are temperature sensors, strain sensors, biosensors, environmental sensors, and wearable sensors, etc. Additive manufacturing technologies can fabricate sensors and microfluidic devices with less labor. This paper focuses on various sensors developed by additive manufacturing processes, and their practical application for the particular purpose is reviewed.

Keywords: additive manufacturing (AM); 3D printed sensors; fused deposition modeling (FDM); challenges of additive manufacturing.

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1. Sensor Classification

1.1. Physical sensors.

These can detect changes in physical quantities and transform them into electrical signals that can be used [1]. Tactile, temperature, particle, gas concentration, and radiofrequency sensing are all applications for physical sensors.

1.2. Chemical sensors.

To detect chemical reactions, chemical sensors use electrochemical and optical methods [1]. Chemical sensors printed in 3D are commonly used to detect liquid concentrations, gas concentrations, and pH variations. However, recent studies show that nanomaterials are more often used due to high surface area and high reactive sites [2-11].

1.3. Biosensors.

The majority of biosensors are used in biological science. Biosensors are primarily used in medical science, food manufacturing, and marine applications. For selective analysis, biosensors use biochemical, molecular recognition properties [12].

2. Additive Manufacturing Technologies for Sensor Fabrication.

Stereolithography, Polyjet, Fused Deposition Modeling, Selective Laser Melting, Selective Laser Sintering, 3D Printing, and 3D Inkjet/Extrusion are examples of sensor fabrication technologies. Fused Deposition Modeling is the most commonly used of these technologies due to its low material cost.

2.1. Fused Deposition Modeling (FDM).

FDM technology is the most dependable and cost-effective form of fabrication. The FDM process uses the content efficiently, resulting in less waste. FDM can be used for a variety of thermoplastic polymers [13]. Poly Lactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Polycarbonates (PC), Polyetheretherketone (PEEK), and Polyetherimide (PEI) are some of the most commonly utilized products.

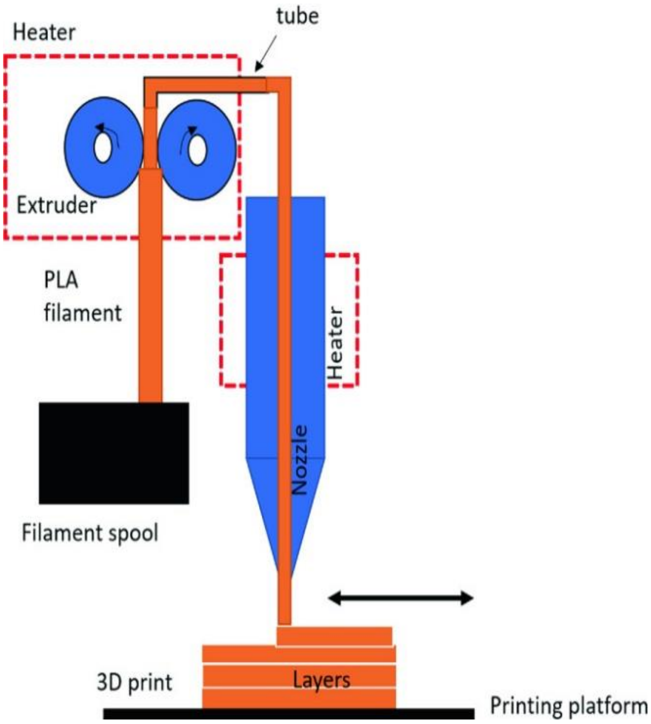

Figure 1. Fused Deposition Modeling Process [13].

FDM is a hot-melt extrusion process that usually uses a filament feedstock with a diameter of 1.75 mm to 3 mm. A drive gear mechanism feeds the filament to the printer. At the heated liquefier, the filament is melted, and the material is deposited layer by layer according to the CAD results. The diameter of the FDM nozzle is 0.4 mm, while the diameter of extruded threaded ranges from 0.1 to 0.4 mm. FDM's mean working temperature varies from 250 to 500 ^{0}C. During the printing process, the print head will travel in an X-Y direction to finish printing a single sheet, then the platform will be lowered in a vertical Z-direction to print the next layer, and so on until the entire object has been printed.

3. Applications of 3D Printing in Biomedical Diagnostics

3.1. Sample pretreatment

It is necessary for diagnostics to reduce the process's complexity and increase the sample's sensitivity [14]. The microfluidic system depicted in Figure 2A has cell flow near the inner wall of the tube, which separates platelets and blood cells from plasma.

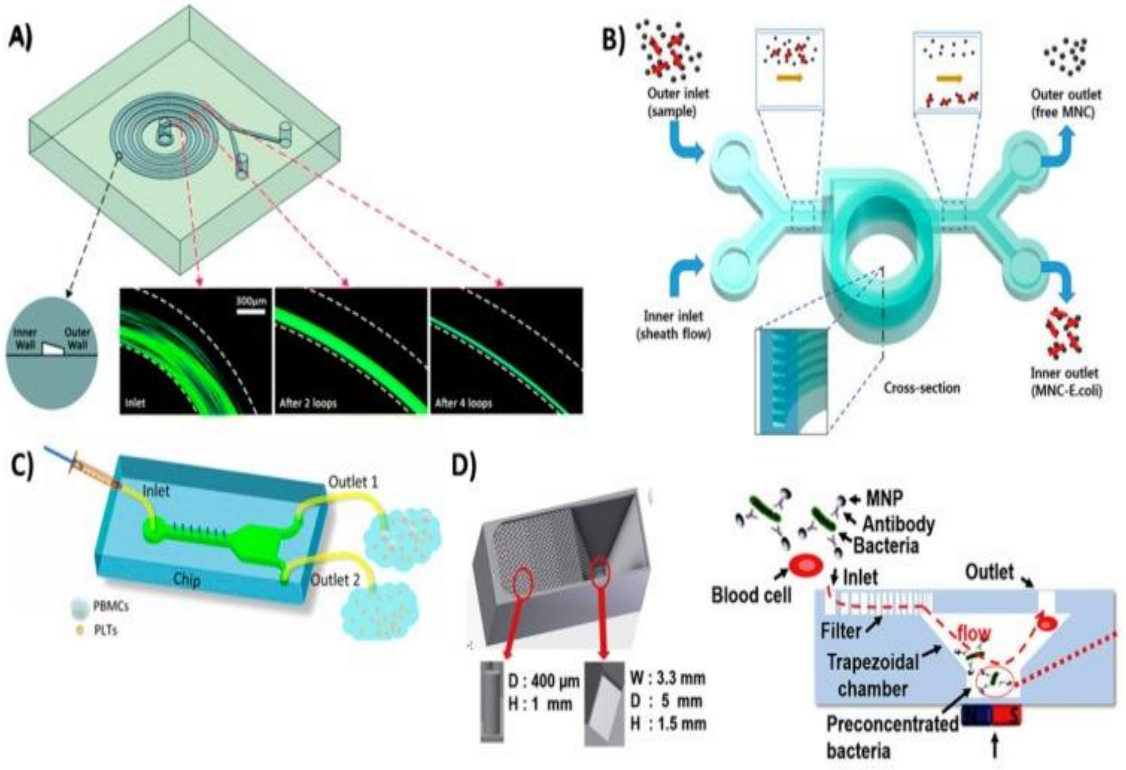

Figure 2. (**A**) Microfluidic device to separate platelets and blood cells from plasma; (**B**) Microfluidic device to separate magnetic nanoclusters coupled to bacteria *E. coli*; (**C**) Microfluidic channel to separate platelets from blood cells; (**D**) Trapezoidal filter with a microfluidic channel [14].

The microfluidic system used to isolate pathogenic bacteria *E. coli* from milk samples is shown in Figure 2B. The theory is based on the separation of free magnetic nanoclusters from bacteria-bound nanoclusters during the flow of magnetic nanoclusters through microfluidic channels. The microfluidic channel in Fig 2C separates platelets from blood cells with 100% purity, using a syringe to pass the blood sample to the device manually. The trapezoidal filter with a microfluidic channel shown in Fig 2D was used to isolate the magnetic nanoparticles from the blood sample.

3.2. Microfluidic flow devices.

Microfluidic flow systems are compact fluidic instruments that can monitor the handling of extremely small samples and assay reagents. AM methods can be used to fabricate microfluidic systems more efficiently and at a lower cost. Figure 3A shows a microfluidic device for calculating the viscosity of a blood sample that is less costly than industrial viscometers [14]. The microfluidic system in Figure 3B has two key functions. The detection chamber will detect the developed luminescence after the adenosine triphosphate sample is mixed with the luminescence reagent mixture. A 3D printed microfluidic chip to detect cancer biomarker proteins is shown in Figure 3C. The proposed design will reduce the assay time to

30 minutes. The microfluidic device in Figure 3D is used to monitor the flow of samples and assay reagents manually.

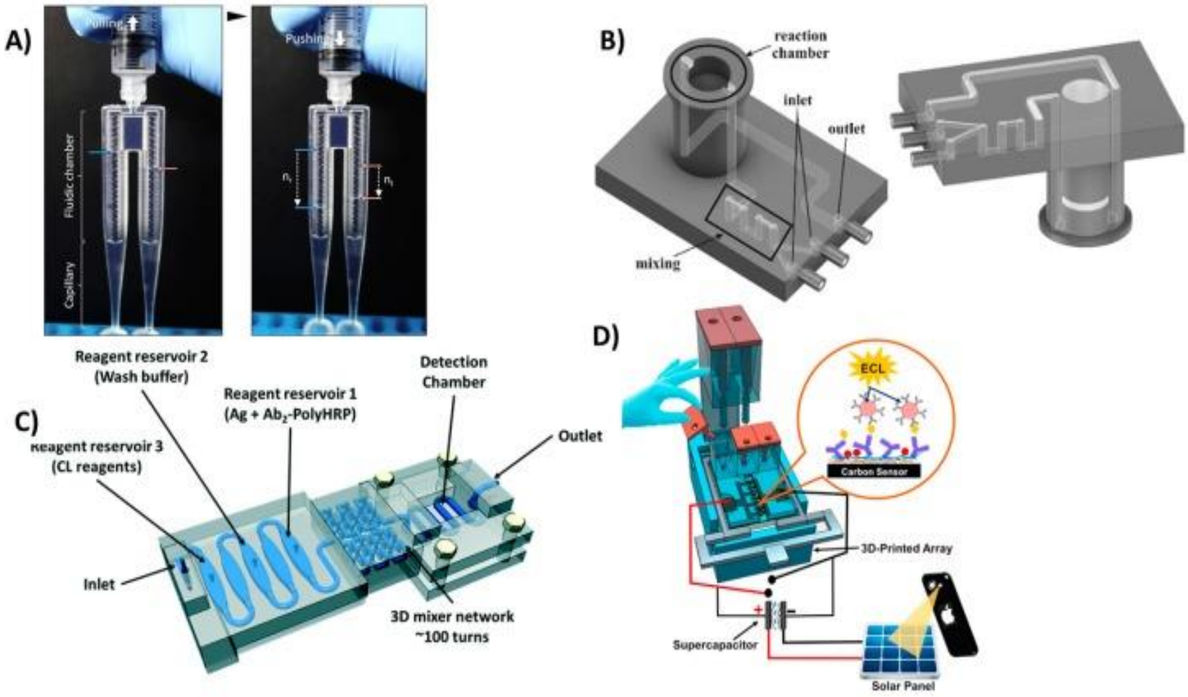

Figure 3. (**A**) 3D Printed syringe for blood viscosity measurement; (**B**) 3D Printed microfluidic device for quantification of adenosine triphosphate; (**C**) 3D Printed microfluidic chip to detect prostate-specific antigen (PFA) and platelet factor-4 (PF-4); (**D**) 3D Printed microfluidic unit that controls the flow of assay reagents and samples [14].

Chemical flow analysis, hematological analysis, electrochemiluminescence DNA tests, and salivary cortisol detection may all benefit from 3D printed microfluidic flow instruments.

4. Engineering Applications of 3D Printed Sensors

4.1. Strain sensor.

Mohammad Reza Khosravani *et al.*, in their publication, discussed 3D printed strain sensors and tactile sensors. Tensile and compressive strains are converted into useful electrical signals using this device. These sensors were created using a stretchable conductive material and a flexible conductive material [15]. The direct ink writing (DIW) method, similar to the FDM technique, is commonly used for fabricating strain sensors. The strain sensor explained by Mohammad Reza Khosravani *et al.* [15] was created by embedding silicone elastomer and piezoresistive inks. These sensors have excellent stretchability and can withstand mechanical strains of up to 800%, and they have a gauge factor of 3.8±0.6, which is comparable to traditional strain gauges.

4.2. Acceleration sensor.

The acceleration sensor is made by printing on polyethylene terephthalate, which gives the sensor more flexibility [15]. The structural substance is a silver paste, and the sacrificial substrate is polyvinyl alcohol. In their publication, Mohammad Reza Khosravani *et al.* described the details of the six-sided gaming die, which includes a microprocessor and an accelerometer, which was 3D printed. The die will be able to sense motion and recognize top surfaces using gravity.

4.3. Pressure sensor.

Mohammad Reza Khosravani *et al.* [15] discussed pressure sensors that can detect changes in pressure and load. It's a beam-based structure made with the FDM method. Changing the diameter of the various printed components allows for differential pressure measurement. Changes in friction, bending, and the fabricated sensors can also detect twisting moments.

4.4. Particle sensor.

Particle sensors are used to determine the content of particles in the atmosphere since they can detect particulates found in the air. Environmental factors can influence the sensors' precision. Mohammad Reza Khosravani *et al.* [15] discussed particle sensors in which 3D printing technology is used to build microchannels. The output of the sensor was calculated by delivering particles to the flow channels using a Quartz Crystal Microbalance (QCB) sensor attached to the microchannels.

5. Applications of AM Technologies

Carmen M. Gonzalez-Henriquez *et al.*, in their publication, showed how AM technologies are used in a variety of industries, including automobile, electronics, aerospace, sports, jewelry, mold making, and architecture [16]. AM technologies have recently become very common in biomedical and medical diagnostics, dentistry, and surgical instruments. AM innovations have shown the ability to create completely personalized goods at a lower cost. The various application areas of AM technologies explained by Samad M. E. Sepasgozar *et al.* [17] are illustrated in Figure 4.

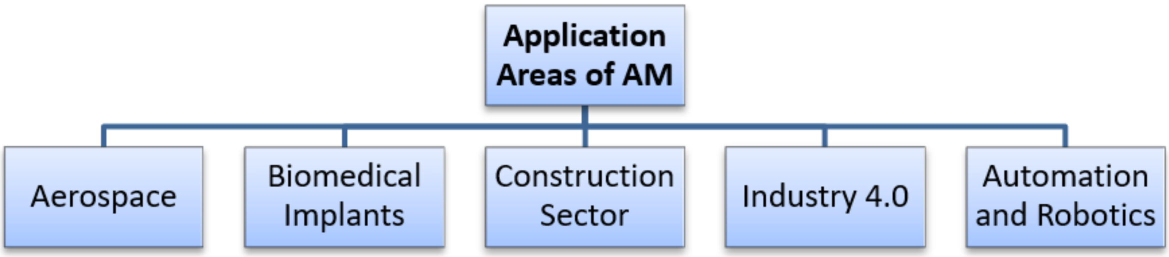

Figure 4. Applications of AM Technologies [17].

6. Challenges of Additive Manufacturing

6.1. Safety.

Waste disposal, material handling risks, and radiation exposure are all risk factors associated with AM technologies. All operators are required to complete safety training.

6.2. Technical know-how.

This relates to the AM sector's specific expertise. The ASTM established standards that covered test methods, AM materials, health and safety precautions, AM science and innovation, and industrial applications of AM. Prior training is required for all operators who wish to use the AM equipment.

6.3. Data security.

Software packages for creating stereolithography files and generating tool path commands are embedded in AM technologies [18]. All AM machines can accept STL files, but tool path commands differ from machine to machine, and only the manufacturers of AM machines are aware of this.

6.4. Post-processing challenges.

Separating a component from its base plate and surface finish and deburring are both post-processing issues. In addition, the method for removing the supports can influence the final product's dimensional accuracy.

6.5. Sustainability.

During the processing of the metal powder, the unused metal powder is recycled. Due to the formation of agglomerated powder during the laser melting process, this job is a little difficult.

7. Studies on Sensor Applications

Table 1. Studies related to Applications of Sensors.

Author	Year	Type of sensor	Applications
Mohammad Vaezi [19]	2012	Capacitive Pressure Sensor	To measure gas or liquid pressures in jet engines
R Shashanka *et al.* [20]	2013	Silver Nanoparticle/Carbon Paste Electrode (AgNps/CPE) sensor	To detect uric acid in the presence of dopamine at physiological pH.
Kenry *et al.* [21]	2016	Polyurethane dispersed stretchable strain sensor	The stretchable strain sensors are attached to different facial and body parts and can detect and monitor skin strains and muscle movements during facial expressions and daily activities.
Dirk Lehmhus *et al.* [22]	2016	Fıbre Optical Sensor	Structural Health Monitoring.
M.T. Rahman *et al.* [23]	2016	Capacitive touch sensor	Measurement of capacitance in touch as well as in untouched state.
Arkadeep Kumar *et al.* [24]	2017	Microfluidic Sensor	Used for actuation of soft robotic grippers.
JuYoun Kwon *et al.* [25]	2017	Potentiometric Sensor	To monitor sodium levels in real-time.
John O'Donnell *et al.* [26]	2017	Screen printed glucose and lactate biosensor	Utilized in cell toxicity studies.
Sepehr Nesaei *et al.* [27]	2018	Glucose biosensor	Used in diabetes management.
Yanglong Lu *et al.* [28]	2018	Physical Based Compressive Sensor (PBCS)	To measure the temperature distribution of manufacturing processes.
Jinke Chang *et al.* [29]	2018	Flexile strain sensor/ piezoresistive sensor	To sense the change of resistance at different hand positions.
Rafiq Ahmad *et al.* [30]	2018	Radiation Sensor	Positron Emission Tomography (PET), Single Photon Emission Computed Tomography (SPECT).
R Shashanka *et al.* [31]	2018	Linear Sweep Voltammetry (LSV) Sensor	To determine the phenomenon of pitting corrosion in stainless steel.
Yan Li *et al.* [32]	2019	Graphene aerogel based flexible sensor	Used in finger motion manipulation auxiliary apparatus.
D. Wolozny *et al.* [33]	2019	3O-C12 living biosensor	To diagnose lung infections.
R Shashanka *et al.* [34]	2020	Cyclic Voltammetry Sensor	Electro generation and deposition of Copper oxide (CuO) nanoparticles.
Xiaofan Ruan *et al.* [35]	2020	Portable microfluidic device sensor	Used in continuous monitoring of human microdialysate.

Author	Year	Type of sensor	Applications
Mahshid Padash *et al.* [36]	2020	Iontophoretic biosensor	Used in alcohol monitoring systems.
Jose Munoz *et al.* [37]	2020	Graphene/ PLA biosensor	Used for the analysis of glucose in blood plasma using chronoamperometry.
Fernando Otero *et al.* [38]	2020	Sweat glucose sensor	To measure glucose level, humidity, pH, and temperature.
Moe Elbadawi *et al.* [39]	2021	Calorimetric Sensor	Used to monitor glucose and Cholesterol levels
Jyoti *et al.* [40]	2021	3D printed nanocarbon electrode sensor (3DnCE)	To detect chlorophenols and nitrophenols in aqueous solutions
David T. Bird *et al.* [41]	2021	Gastric Resident Electronics (GRE) device	Used in personalized diagnostics and treatment of soldiers
Priya Kishor Dave *et al.* [42]	2021	Electrochemical MERS-CoV Sensor	Used to detect MERS-CoV based on a competitive assay
Thanyarat Chaibun *et al.* [43]	2021	Electrochemical biosensor coupled with rolling circle amplification (RCA)	Highly sensitive and specific detection of SARS-CoV-2
Fahad Alam *et al.* [44]	2021	Smart Contact Lenses (CLs)	To detect and continuously monitor the glucose concentrations in tears of diabetic patients.

8. Conclusions

3D printing has many advantages over traditional methods, particularly when it comes to commercial goods. 3D printed sensors have shown increased sensitivity and compatibility with a wide range of personalized items. Fused Deposition Modeling is one of the most promising methods for producing low-cost, high-productivity sensors. With extreme dimensional precision, the FDM process can create critical geometries and cavities. As opposed to traditional methods, 3D printing is most useful in biomedical diagnostics because the testing time is steadily reduced. The use of sensor-based technology can easily measure mechanical parameters such as force, velocity, acceleration, strain, and bending moments, which can help engineers solve critical problems in less time.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgments

The authors declare no acknowledgments.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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