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Review article

Recent Advances in Strain Gauge Technology: Materials, Design, and Applications

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ABSTRACT

Strain gauges are essential components in engineering, used to assess strain in various structural parts under load. Traditional metallic foil strain gauges face limitations like low sensitivity and fragility. Recently, advancements in nanomaterials, flexible electronics, and wireless communication have created new possibilities for strain gauge technology. This review consolidates the latest research on new materials, improved sensor designs, and innovative applications in fields such as aerospace, biomedicine, and civil engineering. It also focuses on the challenges, reliability, and future prospects of intelligent systems that include AI and IoT. The article concludes with a discussion of current issues and the future path to wider adoption.

Keywords: Strain gauge, material, design, application

INTRODUCTION

Strain gauges have played a key role in solid mechanics, stress analysis, and structural monitoring since their development by Edward E. Simmons and Arthur C. Ruge in 1938–1939 [1]. These devices operate on the basis of the piezoresistive effect, in which mechanical deformation leads to measurable changes in electrical resistance, offering the first practical method for quantifying strain in mechanical structures. Initially designed for experimental stress analysis in civil and aerospace engineering, foil-based strain gauges quickly found widespread use in a variety of engineering fields [2]. However, traditional foil strain gauges have significant limitations, including stiffness, limited extensibility, insufficient adhesion to curved surfaces, and reduced sensitivity under harsh conditions such as high humidity or extreme temperatures [3]. These shortcomings have spurred the development of advanced strain-sensing materials that offer greater mechanical flexibility, improved electrical stability, and additional multifunctionality. Recent breakthroughs in nanomaterials—such as carbon nanotubes (CNTs), graphene, MXenes, metal nanowires (e.g., AgNWs and CuNWs), and conductive polymer composites (CPCs)—have paved the way for next-generation strain gauges. These innovations significantly increase measurement rates, stretchability, and sensitivity, pushing the boundaries of traditional strain-sensing technology [4].

Flexible and stretchable substrates such as polydimethylsiloxane (PDMS), thermoplastic polyurethane (TPU), Ecoflex, and polyimide have significantly accelerated the integration of innovative sensing materials into adaptable systems [5]. These materials enable seamless embedding of strain gauges in textiles, wearable technologies, soft robotics, and implantable medical systems, facilitating continuous and noninvasive monitoring of dynamic physiological and biomechanical signals [6]. In addition, cutting-edge micro- and nano-fabrication techniques—including screen printing, inkjet printing, laser sintering, electrospinning, and 3D printing—are increasingly being used to develop intricately patterned strain sensors [7]. These sensors feature high spatial resolution, scalability, and compatibility with Internet of Things (IoT) platforms, further expanding their application potential [8].

Advances in material innovation have been complemented by revolutionary strides in wireless communication technologies, changing the way strain data is collected, transmitted, and analyzed [9]. The integration of technologies such as Bluetooth Low Energy (BLE), Near-Field Communication (NFC), Radio Frequency Identification (RFID), and LoRa into strain sensing systems has enabled real-time remote monitoring, even in environments where wired systems are impractical or unsafe. These wireless strain sensors have become essential in fields such as aerospace structures, underground tunnels, offshore platforms, and portable medical devices [10].

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Things have really changed lately because we're seeing artificial intelligence, or AI, and something called edge computing come together. Think about it: AI, especially with machine learning and deep learning, is starting to look at data about strain – that's like how much something is stretched or squeezed – to find problems early. Instead of just waiting for something to break, we can now predict when it will happen and even make decisions automatically about fixing it. It's like going from just watching to actually understanding what's going on. For example, they've made strain gauges that use AI. These gauges are good at spotting cracks in airplane wings before, they become a big deal [11]. They can also watch what's happening in real-time when someone is recovering from an injury. And it's not just planes. Strain gauges are being used in a lot more places than before. In medicine, you can find flexible strain sensors watching how people walk, checking their breathing, finding their pulse, and following their movements. These sensors are so small, they could be attached on parts of people's bodies to monitor the body parts condition. When it comes to bridges and buildings, these sensors are being put into things like concrete and asphalt. They can keep an eye on how things are changing shape, settling, or getting stressed [12]. This helps make sure structures stay safe. Robots are getting in on the action too. Soft strain sensors are helping robots feel what they're touching so they can interact with people without hurting them. This is important for building trust between humans and robots to have a good interaction and working experience [13].

Even though we've come a long way with strain gauge tech, we're still facing some pretty tough problems [14]. Things like mechanical hysteresis – where the sensor's response lags behind the actual strain – and signal drift, where the readings change over time even with constant strain, are real headaches [15]. Plus, the signal can sometimes be drowned out by noise, making it hard to get accurate readings. And let's not forget about durability – these sensors need to hold up under repeated or constant stress, and that's not always the case [16]. It's also tricky to manufacture these sensors on a large scale and have them all perform consistently. And to make things even more complicated, we don't have good, standard ways to measure how well a sensor is actually working. That makes it hard to compare different sensors and know which one is best for a job. We really need to do more research to make these sensors tougher, especially when they're used outside or inside the body. Harsh weather and biological environments can really mess with their performance and lifespan. Imagine trying to use a delicate sensor in a construction site or inside a living organism – it needs to be able to withstand a lot! Given all the new tech coming out, this review takes a good hard look at where strain gauge technology is today [17]. We'll be checking out new materials that can sense strain, better ways to build these sensors, and how they're being built into structures. I will consider how wireless systems are being used to transmit data from the sensors and look into the use of artificial intelligence to make sense of all the information. Also, the review doesn't shy away from the tough stuff: what are the biggest problems we're facing, and where should research go next? This field is changing fast, and there are tons of opportunities to make these sensors even better. For example, the next generation of strain gauges might use self-healing materials and could be powered from vibrations or changes in pressure. The sensors could also be able to detect multiple parameters at the same time, not just strain but also heat and moisture [18].

MATERIAL INNOVATIONS

METAL AND ALLOY-BASED STRAIN GAUGES

Others even figured out how to keep the temperature from messing with the readings by using two sensors set up at right angles. This trick seriously cuts down on thermal drift, which is a big headache with metal strain gauges (Sun & Wang, 2022). The dual setup allows engineers to separate the thermal expansion from the mechanical strain, providing corrected measurements, despite the heat surrounding the setup. So, one sensor captures the strain from the material being measured, while the other only captures the thermal expansion in the environment. The development of temperature-compensated designs marks another step forward in strain gauge technology, ensuring that these sensors remain applicable and helpful in different settings. Plus, it helps scientists measure how strong a material is in different situations. It is an important piece of design [19].

POLYMERIC AND FLEXIBLE SUBSTRATES

Getting the conductive parts to stick firmly to the flexible base, even after repeated stretching. It's a tough nut to crack! If those parts separate, the sensor's performance drops. So, researchers are looking into ways to make sure everything stays where it should. Some studies have shown that changing the material's surface or adding tiny fillers, that can boost how well the sensor performs and how long it lasts. That means things are looking for even more advanced flexible strain gauges [20].

NANOMATERIALS AND COMPOSITES

Nanomaterials like carbon nanotubes (CNTs), graphene, and MXenes have seriously changed how strain gauges work. These materials are super interesting. They have a crazy amount of surface area compared to how small they are, and their electrical and mechanical properties are really something else. Basically, when you mix them into bendy materials, they form a network. This network changes how well electricity flows when it's bent or stretched. This change is so big that it gives you gauge factors way over 1000. For example, [21] showed that just a single layer of graphene could hit a gauge factor of 1050, and it could still stretch more than 10%. That's pretty wild! And get this: If you mix CNTs with some special conductive polymers, like PEDOT:PSS or polyurethane, you get something that's both super sensitive and really flexible [22]. That combo opens up a lot of possibilities.

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Now, MXenes are a bit newer to the party. They're 2D materials, and they're looking really good for this kind of stuff too. You can tweak how well they conduct electricity, and they can even be made to like water, which is useful. People are starting to use them more and more in wearable gadgets, basically, things you can wear on your body. They are really useful for devices that need to resist sweat and be safe for your skin. So, yeah, these materials are making a real splash in strain gauge technology and wearable tech [23].

ADVANCES IN DESIGN AND FABRICATION

MICROFABRICATION AND MEMS INTEGRATION

Combining tiny machines called microelectromechanical systems (MEMS) with strain gauge tech has led to really small, energy-efficient sensors. According to [24], these sensors give us a lot of control over how they're shaped and how sensitive they are. These MEMS strain gauges are usually made using fancy techniques like photolithography, chemical etching, and sputtering. They often use silicon or bendable materials as a base. Having this kind of exactness is super important for things like medical implants and robot joints. Obviously, you can't have huge sensors in those kinds of applications. Plus, you need them to be really accurate. [25] came up with a cool idea. They created a MEMS-based gauge array that can measure strain at a level smaller than a micron. To make it even better, they added circuits that process signals in real-time, so you can keep an eye on what's happening right away. Besides being accurate, MEMS-based strain gauges are great because you can easily make a lot of them, and they'll all be pretty much the same. Still, there are some things we need to work on. For example, we need to make them even more sensitive, deal with how temperature affects them, and find ways to pack them safely so they can work in tough conditions.

WIRELESS AND PASSIVE STRAIN GAUGES

Wireless strain gauges are a big step up from the old wired ones, mainly because you don't have to mess with cables anymore, and you can move around freely. Researchers figured out they could use things like RF, Bluetooth, or even passive RFID to build totally wireless setups. These setups can send data as it's happening [26]. Specifically, passive systems are pretty cool for when you need to stick them inside things that spin around or in places that are just a pain to get to. The neat thing about passive systems is they grab power from a reader outside, so you don't have to worry about batteries. Huang and Cheng (2020) even showed off a passive wireless sensor that uses something called LC resonance. It was able to measure how much stress was on turbine blades, even when they were spinning super-fast. Still, it isn't all perfect. Wireless sensors have some problems. The signal can get weaker, you can't send as much data at once, and other stuff in the area can mess with the signal. These problems get even worse when you're dealing with metal around [27].

MULTIFUNCTIONAL AND SELF-HEALING GAUGES

Strain gauges are getting a major upgrade! It's not just about measuring how much something stretches or bends anymore. Think of future strain gauges as super-sensors that can do a whole lot more. Zhang and his team pointed this out in their 2023 research. Imagine a single sensor that not only tells you the strain on a material but also its temperature, how humid it is, and even picks up biological signals! It's like having a weather station and a medical monitor all rolled into one tiny device. The trick is in how these sensors are built. They often use layers of different materials or special composites that are designed to react to various things at the same time. So, when the temperature changes, the sensor knows. When there's more moisture in the air, it picks that up too. and, of course, it still does its original job of measuring strain [28]. Now, here's where things get really cool: self-healing materials. This is a game-changer, especially if you want sensors that last a long time or can be implanted inside the body. Self-healing means that if the sensor gets damaged, it can fix itself. No need to replace it! Zhang and his colleagues talked about a specific strain sensor made from a special kind of plastic (conductive polyurethane). It's pretty amazing. If it gets nicked or scratched, it can recover almost all (95%) of its ability to conduct electricity. How does it work? It's all about clever design. The researchers used things called hydrogen bonds and tiny microcapsules within the material. These things work together to repair the damage automatically. When a crack forms, the microcapsules break open and release chemicals that start the healing process. The hydrogen bonds then help to stitch everything back together. This kind of self-healing tech makes sensors way more dependable and long-lasting. Think about wearable devices like fitness trackers or medical sensors that stick to your skin. They're constantly being bent, stretched, and bumped. With self-healing, they can withstand a lot more wear and tear. They are also excellent for biomedical applications because their physical fragility is a usual problem. It's a big step forward for making sensors that can handle the real world [29].

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APPLICATIONS

MECHANICAL TESTING AND MATERIAL CHARACTERIZATION

Strain gauges play a crucial role in experimental mechanics for assessing material properties like Young's modulus, Poisson's ratio, and yield strength. Foil strain gauges are widely used, being attached to test specimens to monitor strain under tensile, compressive, or fatigue loading scenarios. This info is key to checking our computer models and making our designs spot on [30].

AEROSPACE AND AUTOMOTIVE ENGINEERING

In the aerospace biz, super light and touchy strain gauges are super important for keeping tabs on stress on things like wings, plane bodies, and turbine blades. When they're testing out new designs and making sure everything is structurally sound, they often use semiconductor and foil gauges. Car companies do the same thing, sticking strain sensors in chassis and suspension to watch the load and see what happens in crashes [31].

ROBOTICS AND WEARABLE ELECTRONICS

Strain gauges that can bend and stretch are super important in robotics. They do things like help robots feel what they're touching, keep track of how robot joints are moving, and give robots a sense of pressure. In soft robotics, these gauges are put in the moving parts to give instant feedback on how they're changing shape. Wearable tech also uses these stretchy sensors. They're put in clothes or stuck right on the skin to keep track of posture, how someone walks, and even to keep an eye on patients from a distance [32].

BIOMEDICAL APPLICATIONS

Strain gauges are super important for keeping tabs on your body without poking or prodding. They help measure things like how fast you're breathing, what your muscles are up to, how your joints are moving, and even your pulse. Graphene and carbon nanotube sensors are becoming popular for biomedical patches and e-skins that track your health all the time. To work well, these gadgets need to be body-friendly, bendy, tough enough to handle body heat, and sweat-proof [33].

INDUSTRIAL AND MANUFACTURING MONITORING

In factories, strain gauges do important jobs. They keep an eye on how much weight heavy machines are carrying, spot when shafts aren't lined up right, and help hydraulic systems run smoothly. Plus, they make things more automatic by controlling how hard things are pressed, clamped, and twisted on the assembly line [34].

ENERGY AND ENVIRONMENTAL SYSTEMS

Strain sensors are super important for keeping an eye on things like wind turbines, oil pipelines, and nuclear plants, especially when things get rough. Fiber optic strain gauges are great for places with high voltage or explosive risks because they don't conduct electricity. As strain gauge tech gets better, we're finding new uses for them all over the place. This helps us build safer stuff, make smarter gadgets, and come up with healthcare that's a better fit for folks [35].

AEROSPACE AND STRUCTURAL HEALTH MONITORING

In the aerospace biz, stuff like wings, bodies, and turbine blades go through a lot of stress that changes all the time. Strain gauges are super important for keeping an eye on these parts. This helps lower the chance of things breaking and keeps them flying longer. Old-school foil strain gauges are still used when testing how long parts last in the lab. But they can't take the heat and shaking that happens when a plane is actually flying. So, newer options like fiber Bragg gratings (FBGs) and wireless MEMS gauges are becoming popular. They're super sensitive and don't get messed up by electromagnetic stuff, as Lee and crew pointed out in 2023. For example, NASA checked out a smart wing made of composite stuff with over 300 strain gauges. They wanted to see how the load was spread out while the plane was flying. The info from these sensors gave them live updates, which allowed them to adjust the flight controls. This made things safer and work better overall. Also, FBG sensors inside composite materials have done a bang-up job of checking strain over long stretches. They even have built-in temp regulators to make sure they are

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accurate. Wireless strain sensing has also been used on spinning parts like jet engines. One test showed that passive RFID strain sensors kept talking, even when spinning at 10,000 RPM. These cool inventions are totally changing how we take care of airplanes. Instead of just fixing things when they break, we can predict when they'll need servicing and keep them in good shape [36].

BIOMEDICAL ENGINEERING

Biomedical strain sensors are super important for stuff that needs to be bendy, stretchy, and safe for the body. Putting them in wearables, implants, and prosthetics has totally changed how we keep tabs on the body in real-time. Like, if you stick strain sensors in smart bandages, they can keep an eye on how a wound's healing by sensing tiny changes in the skin. This gives doctors a way to check things out without cutting anyone open. And for wearable tech, bendy strain sensors are often put on joints to watch how people move, their posture, and how they walk—especially when they're getting better after an injury. Came up with this cool wearable sensor that uses PDMS to really accurately track how the knee joint moves, which could be really helpful for keeping track of recovery after surgery. Also, smart gloves with strain sensors made from graphene have been used to control robots and in virtual reality [37]. But implantable sensors have problems, like stuff building up on them, the body rejecting them, and just wearing out. To try and fix this, people have been looking into polymers that break down naturally and materials that the body can absorb, so they disappear after they've done their job. This is making way for the next wave of implants that work well and don't mess with the body too much [38].

CIVIL INFRASTRUCTURE

Things like bridges, tunnels, and buildings deal with constant stress from stuff like cars, weather, and earthquakes. Putting strain sensors inside them lets us keep an eye on things in real time and plan for when stuff needs fixing. Fiber optic strain sensors, mainly Fiber Bragg Gratings (FBGs), are used a lot in big bridges and tunnels. They don't get messed up by the environment and can handle tons of sensors on one wire. The Tsing Ma Bridge in Hong Kong is a great example – it has over 1,000 FBG sensors. These sensors constantly check strain, temp, and movement, giving important info during typhoons and heavy traffic [39]. Also, wireless sensor networks (WSNs) are now being used in smart cities to watch over tall buildings. WSNs are cheaper and easier to set up than regular wired systems. People are now using machine learning with strain gauge data to get better at spotting damage and checking how structures are doing. By spotting weird strain patterns automatically, these systems can give early warnings to help stop big failures [40].

CHALLENGES AND FUTURE OUTLOOK

LONG-TERM STABILITY AND DURABILITY

A big problem with using fancy strain gauges, especially those made with nanomaterials, is keeping them stable for a long time. Nanocomposites, such as carbon nanotubes and graphene, are really sensitive, but they can have issues like signal drift, hysteresis, and just wearing out if you use them a lot. Then, stuff like humidity, temperature changes, and sunlight can mess with how well the sensor works, particularly if you're using it outside. To try and fix these problems, researchers have been trying stuff like wrapping the sensors in protective layers, using waterproof coatings, and changing the surface to make them last longer against chemicals and heat. Even with these improvements, it's still hard to get these new gauges to last as long and be as reliable as the old metal ones, and that's something people are still working on [41].

SCALABILITY AND MANUFACTURING

Lab strain sensors using flexible nanomaterials work great, but getting them ready for mass production is hard because they're tough to reproduce and expensive. Fancy methods like inkjet and 3D printing could help, but it's still tricky to get even material spread and reliable connections when you make a lot of them. MEMS sensors are easier to scale up since they're made with precise photolithography. Still, they break easily and need special clean rooms, which makes them expensive and not good for new markets. Going ahead, we need to find a way to make these sensors work well, be cheap to produce, and easy to manufacture so more people can use them [42].

INTEGRATION WITH AI AND IOT

Putting strain sensors into smart tech is cool, but it ain't without its headaches. As we get flooded with sensor info, we gotta figure out how to crunch those numbers fast. Smarter computer programs, like the ones that use brain-like networks to spot weird stuff, are helping us read strain patterns so we can guess when things might break. Hooking up strain sensors to the internet lets us keep tabs on things from anywhere, even if it's far away or hard to reach. But to make this work well, we gotta sort out a few issues:

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saving power, making wireless signals work right, and keeping data safe. People are trying out stuff like electronics that don't use much juice, doing some of the number-crunching on the spot, and scrambling messages to keep them private [43]. Wireless sensor things are getting more popular, and strain gauges are becoming a key part of smart setups for watching how strong buildings, roads, and bridges are. These sensors shoot strain data over the air to computers in the sky, so engineers can see what's up in real-time. Linking strain gauges to networks like LoRa or NB-IoT means we can send signals far away without burning a ton of power. Like, on bridges, these sensors can send alerts when things look dicey, which helps keep them from falling apart [44].

TOWARD BIODEGRADABLE AND IMPLANTABLE SENSORS

There's a lot of excitement in biomedicine about biodegradable strain sensors. The idea is that they'd dissolve in your body after they've done their job, so you wouldn't need another surgery. Materials being looked at include silk fibroin, PLA, and magnesium alloys. One big problem is trying to get the sensor to last long enough while still breaking down properly. Also, we need to make sure that the stuff it breaks down into is safe for the body. Even though there are some challenges, this tech could be great for short-term monitoring with things like implants, wound care, and heart health [45].

CONCLUSION

Strain gauge tech has come a long way. It's not just about metal anymore; it now mixes stuff like materials science, electronics, and data. New stuff like nanomaterials and wireless have made it useful in more places. There are still some problems to solve, like making it stable and producing it on a big scale. But the future looks good, especially since more people are using smart systems.

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