Piezoelectric Materials, Determinant of the 21st century Smart Industry: A Review

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Abstract- Piezoelectric materials as determinants of 21st century smart industry were reviewed with the aim of showcasing how utilization of their properties defines 21st century smart industries. Secondary data was used for the study. The study focused on few key properties: piezoelectric coefficient and mechanical quality factor. It was observed that when mechanical stress is applied to piezoelectric material (quartz, lead zirconate titanate (PZT), Rochelle salt, barium titanate, polyvinylidne fluoride (PVDF)), electrical charges are generated. The electrical charges generated causes mechanical motion. The sensing of the electrical charges (sensor) and the causing of mechanical motion (actuator) in these materials is the brain behind automation in 21st century industries and robotic engineering. The ability to detect this relationship is the piezoelectric coefficient. While the mechanical quality factor is the ability to store generated electrical energy. The utilization of this property is also the brain behind smart cities green energy and self sustaining tools. The study was able x-ray properties of piezoelectric materials and how they are shaping 21st century smart industries.

Keywords: Piezoelectric Materials, Mechanic Quality Factor, Smart Industry, Piezoelectric Coefficient

I. INTRODUCTION

Smart materials are materials that have the ability to respond to stimuli in controlled fashion in a reversible manner. They respond to temperature, pressure, moisture content, pH etc changes (Brizi, *etal.,* 2023). Piezoelectric materials are one class of such materials that generate electrical charge in response to mechanical stress (Culshaw, 1996). The electrical charges generated from mechanical stress (Dakhole & Boke, 2017) is utilized for energy harvesting to power small electronics, sensors, and even wearable devices; sensing and actuation in medical devices and robotics; precision and control for providing detailed images of internal body structures *(Ilyas, et al., 2023*); structural health monitoring to detect stress, strain and damages in structures (Chen & Ni, 2018) etc. Piezoelectric materials include quartz, lead zirconate titanate (PZT), Rochelle salt, barium titanate, polyvinylidne fluoride (PVDF) etc. Smart industry also known as industry 4.0 uses piezoelectric and smart materials to provide robotic, medical imageries and other smart services.

The purpose of this article is to x-ray piezoelectric materials properties and how they are applied for the smart industry.

II. PROPERTIES OF PIEZOELECTRIC MATERIALS

Piezoelectric materials have distinctive properties that make them important in the smart industry. These properties include piezoelectric coefficients, mechanical quality factor, material composition, polling, relative permittivity etc. (Wikipedia, 2025; EL-PRO-CUS, nd; Vaia, nd).

2.1 Piezoelectric coefficient: This is the amount of piezoelectric effect in materials. It is the relationship between mechanical stress applied to the material and the electrical charge generated. It is mostly expressed in piezoelectric strain, voltage and stress constants.

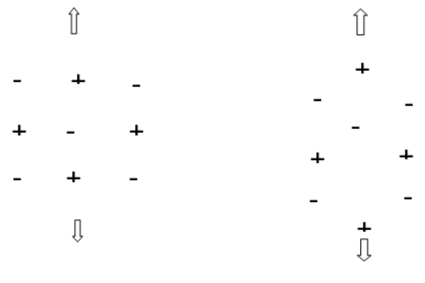

Figure 1, effect of piezoelectric coefficient on materials, the arrows are tensional stresses σ

When mechanical stress σ is applied, an electric displacement D is generated:

$D_i = d_{ij}\sigma_j$ (1)

D_i=Electric displacement (C/m²)
d_{ij}=Piezoelectric coefficient (C/N)
σ_j =Mechanical stress (N/m²)

This is called Direct Piezoelectric Effect, while Converse Piezoelectric Effect is when an electric field E is applied, mechanical strain S is induced:

$S_j = d_{ij}E_i$ (2)

S_j= Mechanical strain (dimensionless)
d_{ij}= Piezoelectric coefficient (m/V)
E_i = Electric field (V/m)
d_{33} = Strain in the same direction as the applied electric field (longitudinal mode).
d_3 = Strain perpendicular to the applied electric field (transverse mode).
d_1= Shear strain due to electric field.

These coefficients are material-dependent and typically measured in picoCoulombs per Newton (pC/N) or meters per Volt (m/V)

2.2 Mechanical Quality Factor

The mechanical quality factor (Qm) in piezoelectric materials describes how efficiently they store mechanical energy relative to losses. It describes how "cleanly" a resonator stores and returns energy versus how much it loses each cycle. High Qm means slow decay and sharp resonance; low Qm means fast decay and broad resonance. Formally, it is a dimensionless measure of under-damping and can be defined through energy loss per cycle or through resonance bandwidth under steady forcing.

2.2.1 Mathematical Expressions of Mechanical Quality Factor

i. Energy-Based Definition

$Q=2\pi\cdot\frac{E_{\mathrm{s}}}{E_{\mathrm{d}}}$

Where E_{s} Energy is stored (Potential + kinetic energy in the oscillating system)
E_{d} Is Energy dissipated per cycle (Energy lost due to damping (friction, resistance, etc.).

In piezoelectric materials, stored energy is partly mechanical (strain in the lattice) and partly electrical (polarization).

A high Q ensures that most of the mechanical strain energy is converted into electrical energy instead of being lost as heat.

ii. Frequency-Based Definition

$Q=\frac{f_0}{\Delta f}$

Where f_0: Resonant (natural) frequency of the system.

Δf: Bandwidth (difference between frequencies at which power drops to half its peak).

Piezoelectric resonators (like quartz crystals or ceramic transducers) operate at a resonant frequency. A high Q means narrow bandwidth → stable oscillation → efficient conversion of mechanical vibration into electrical signal. A low Q means broad resonance → more damping → less efficient energy conversion.

iii. Damped Oscillator Expression

For a mass-spring-damper system

$Q=\frac{M}{kD}$

Where M: Mass of the oscillator.
k: Spring constant (stiffness).
D: Damping coefficient.

In a damped oscillator, the mechanical quality factor Q is a measure of how efficiently the system stores vibrational energy relative to how quickly it loses it

III. APPLICATIONS

3.1 Sensors and Actuators: Piezoelectric materials act as sensors and actuators *(Zhou, et al., 2024)* in smart Industry works by converting mechanical stress into electrical signals (sensing) and electrical energy into mechanical motion (actuation) (Mangla, 2024), enabling machines and systems to interact intelligently with their environment (Pasupuleti, 2024). Sensors collect real-time data such as temperature, pressure, vibration, or position, which is crucial for monitoring processes and ensuring quality (Sahu, 2023). Actuators, on the other hand, convert control signals into physical actions like movement, rotation, or adjustments in machinery. Together, they create closed-loop systems where sensors provide feedback and actuators execute precise responses. This integration allows automation, predictive maintenance, and adaptive manufacturing, reducing downtime and increasing efficiency. Ultimately, sensors and actuators make industrial systems more responsive, flexible, and capable of self-optimization.

3.2 Energy Harvesting:

Energy harvesting is the process of capturing small amounts of energy from the environment and converting it into usable electrical power (*Brusa, et al., 2023*). Piezoelectric materials play a vital role in energy harvesting by converting mechanical vibrations and stresses into usable electrical energy *(Rajapaksha, et al., 2025).* They are especially effective in industrial environments where machinery produces constant vibrations that would otherwise be wasted. This harvested energy can power small sensors and wireless devices, reducing the need for batteries or complex wiring. Their ability to generate electricity from ambient motion makes them ideal for self-sustaining systems in smart factories. By enabling continuous monitoring without external power sources *(Ria, et al., 2024),* piezoelectric harvesters support predictive maintenance and improve efficiency. Ultimately, they contribute to greener, more sustainable automation by recycling mechanical energy into electrical power.

3.3 Medical Imaging: Piezoelectric materials are essential in medical imaging because they enable ultrasound transducers to convert electrical energy into sound waves and back, providing clear diagnostic images. Their high sensitivity, fast response, and miniaturization capabilities make them indispensable in modern imaging systems.

Piezoelectric ceramics are the core of ultrasound probes, where they generate sound waves when an electric field is applied and detect echoes when mechanical stress returns, producing real-time diagnostic images.

Their ability to produce high-frequency vibrations allows for fine spatial resolution, which is critical in applications like fetal monitoring, cardiac imaging, and tumor detection.

Piezoelectric polymers and composites enable the development of smaller, flexible, and portable imaging devices, making point-of-care diagnostics more accessible.

These materials efficiently convert energy between mechanical and electrical forms, reducing power consumption in imaging systems and supporting longer operation times in portable devices

3.4 Structural Health Monitoring: Piezoelectric materials are central to structural health monitoring because they act as both sensors and actuators. They detect strain and stress and vibrations by converting mechanical energy into electrical signals, which helps identify cracks, fatigue or determination (Brizi et al., 2023). As actuators, they generate ultrasonic waves that propagate through structures and anomalies in these waves reveal hidden image. Their compact size and ability to be embedded in concrete, sometimes in concrete, composites and metals make them ideal for long time monitoring without weakening the host material. They also enable real-time monitoring, allowing engineers to predict failures before they occurred. In additions, piezoelectric systems can harvest energy from vibrations, powering wireless sensors for continuous monitoring. They are widely used in bridges, aircrafts, pipelines and high and rise buildings where safety is critical. By integrating smart systems, they support predicting maintenance strategies that reduce costs and extend service life.

However, challenges such as durability in harsh environments and signal interpretation must be addressed.

IV. CONCLUSION

Piezoelectric materials as determinants of 21st century smart industry were reviewed with the aim of showcasing how utilization of their properties defines 21st century smart industries. Secondary data was used for the study. The study focused on few key properties: piezoelectric coefficient and mechanical quality factor. It was observed that when mechanical stress is applied to piezoelectric material (quartz, lead zirconate titanate (PZT), Rochelle salt, barium titanate, polyvinylidne fluoride (PVDF)), electrical charges are generated. The electrical charges generated causes mechanical motion. The sensing of the electrical charges (sensor) and the causing of mechanical motion (actuator) in these materials is the brain behind automation in 21st century industries and robotic engineering. The ability to detect this relationship is the piezoelectric coefficient. While the mechanical quality factor is the ability to store generated electrical energy. The utilization of this property is also the brain behind smart cities green energy, medical imaging, and structural health monitoring and self sustaining tools. The study was able to x-ray properties of piezoelectric materials and how they are shaping 21st century smart industries.

In the medical industry piezoelectric materials enable ultrasound transducers to convert electrical energy into sound waves and back, providing clear diagnostic images. Their high sensitivity, fast response, and miniaturization capabilities make them indispensable in modern imaging systems. In the monitoring of structures, piezoelectric materials detect strain and stress and vibrations by converting mechanical energy into electrical signals, which helps identify cracks, fatigue or determination.

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