



SMART MATERIALS TECHNOLOGY–BASED PRODUCTS APPLICATIONS IN THE AUTOMOTIVE INDUSTRY

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ABSTRACT

The developments of new and innovative materials are contributing significantly to the large scale such as automotive industry. Century by century uncountable inventions and developments were dedicated to synchronized technological advancement. Smart materials are highly efficient materials and their performance comes at high costs associated with the high level of R&D involved. Therefore, invention of these materials conceptualized to produce effective sensors and actuators according to the purpose. Some everyday items are already incorporating such smart materials, and the number of applications for them is growing steadily. Invention of functional and intelligent materials introduced new concept of intelligent infrastructure systems, autonomous systems, smart structures and robotics in the bygone years. Smart materials include the piezoelectric materials (PZT).

Keywords: automotive industry; innovative technologies; sensors; smart materials; Lead Zirconate Titanates (PZT);

1. INTRODUCTION

Can we imagine “the innovative society” without “the innovative materials” or without their applications? In several industries, including in the automotive industry, the smart and innovative materials will change the look and feel of the cars and they can provide significant benefits when they are used to replace conventional devices by reducing vehicle mass, component size and complexity, and improving design flexibility, functionality and reliability [12,24].

Historically development and advancement of societies have been intimately related to materials and its development. With time, techniques were discovered for producing materials that had properties superior to naturally occurring materials. The development of many technologies that make our life comfortable is closely related to materials [1].

This new century is dedicated to development of materials and development of intelligent infrastructure systems. Accomplishment of this goal necessitates better understanding of available technologies, physical theories, mathematical theories, experimental investigations, solid mechanics and mechanics of materials at various scales, development in materials science and in various other scientific concepts. This historical achievement can be ensured by devoted individuals and synchronized assembly of interdisciplinary researchers. Now, it is a new era of development [2,4,5,20-27]. Even development of new material can open new perspective in these relevant problems. Several small smart structures use actuators and sensors at milli- and micro-scales to achieve a certain goal (active and passive control). Nowadays, there are numerous research activities at universities, companies, and government organizations worldwide. Researchers are constantly finding combinations of technologies to increase avenues for commercialization.

Materials technology created products and components that are smaller, smarter, multifunctional, environmentally compatible, more survivable and customizable. These products will not only contribute to the growing industrial revolutions but will have additional effects on manufacturing logistics and personal lifestyles. Variety of materials known as advanced materials has been developed for different applications [12,16,17,20-27].

To achieve a specific objective for a particular function or application, a new material or alloy has to satisfy specific qualifications related to the following properties [12,22,24]:

- technical properties, including mechanical characteristics such as plastic flow, fatigue and yield strength and behavioral characteristics such as damage tolerance and electrical, heat and fire resistance;



- technological properties, encompassing manufacturing, forming, welding abilities, thermal processing, waste level, workability, automation and repair capacities;
- economic criteria, related to raw material and production costs, supply expenses and availability;
- environmental characteristics, including features such as toxicity and pollution; and
- sustainable development criteria, implying reuse and recycling capacities.

If the functions of sensing and actuation are added to the list, then the new material/alloy is considered a smart material.

As humanity has made great progress in processing elementary materials, they have become milestones that marked the early stages of mankind development. It was only the beginning of the recent hundred years that materials became multifunctional and required the optimization of different properties. With the last evolution, the concept has been driving toward composite materials where two or more distinct material phases are being combined together to provide a better combination of properties. Currently, the next evolutionary step is being contemplated with the concept of smart materials [2,7,8,12,16,21,24-27].

Science and technology have made amazing developments in the design of electronics and machinery using standard materials, which do not have particularly special properties (i.e. steel, aluminum, gold). Imagine the range of possibilities, which exist for special materials that have properties scientists can manipulate [7,8,17]. Some such materials have the ability to change shape or size simply by adding a little bit of heat, or to change from a liquid to a solid almost instantly when near a magnet. These materials are called smart materials.

Smart materials, similar to living beings, have the ability to perform both sensing and actuating functions and are capable of adapting to changes in the environment. In other words, smart materials can change themselves in response to an outside stimulus or respond to the stimulus by producing a signal of some sort. By utilizing these materials, a complicated part in a system consisting of individual structural, sensing, and actuating components can now exist in a single component, thereby reducing overall size and complexity of the system.

2. INNOVATIVE MATERIALS FOR THE AUTOMOTIVE INDUSTRY

The key to 21st century competitive advantage will be the development of products with increasing levels of functionality. “Smart Materials” will play a critical role in this development, where we define these as materials that form part of a smart structural system that has the capability to sense its environment and the effects thereof and, if truly smart, to respond to that external stimulus via an active control mechanism. Due to their high flexibility, versatility and power-to-weight ratio compared with traditional rigid actuators, the smart materials have the potential to be a highly disruptive emerging technology (as distinguished from a conventional technology), as a field of technology that broaches new territory in some significant way, with new technological developments [2,16,21,25].

Smart materials are nowadays being used in all spheres of human life and technology. A lot of research is going on to utilize their potential in various engineering applications which may prove useful for us. A wide variety of smart materials exist, which includes piezoelectric materials, shape memory alloys, etc. One of the foremost challenges in robotics is the development of muscle-like actuators that have the capability to reproduce the smooth motions.[3] The criteria for artificial muscle technologies that allow for specification of new actuator technologies include stress, strain, strain rate, cycle life, and elastic modulus. Thermal actuator-based artificial muscles offer heat resistance, impact resistance, low density, high fatigue strength, and large force generation during shape changes. Artificial muscle technologies have wide potential applications in industrial smart structures as actuators, in robotics, aerospace, automotive industry, medicine, noise control etc. [3] Over the past several decades the Micro-Electro-Mechanical Systems (MEMS) researchers and developers have demonstrated an extremely large number of micro-sensors for almost every possible sensing modality including temperature, pressure, inertial forces, chemical species, magnetic fields, radiation, etc. Surprisingly, even though these micro-actuators are extremely small, they frequently can cause effects at the macro-scale level. New artificial muscles are



enabling diverse technologies. The broad impact of new artificial muscles is potentially analogous to the impact of piezoelectric materials on the global society.

Piezoelectric actuators are also extremely good in positioning applications and are commonly used as sensors and actuators in Micro–Electro–Mechanical Systems (MEMS) devices because of their high sensitivity. While the functional elements are miniaturized structures, sensors, actuators, and microelectronics, the most notable (and perhaps most interesting) elements are the micro–sensors and micro–actuators. The most common applications of this type of material are in actuators and sensors. The majority of historic actuators are made of ceramic piezoelectric materials. One of the most common applications is in the field of robotics in the development of artificial muscles [9,13,15,18,19].

Smart materials are used in number of areas. The potential future benefits of smart materials, structures and systems are amazing in their scope. This technology gives promise of optimum responses to highly complex problem areas by, for example, providing early warning of the problems or adapting the response to cope with unforeseen conditions, thus enhancing the survivability of the system and improving its life cycle. Moreover, enhancements to many products could provide better control by minimizing distortion and increasing precision [7,20,22,24].

Smart materials are being used in the automotive industry already. Automakers are already using sensors and actuators made of smart materials to replace existing motors and mechanical devices used for purposes like adjusting mirrors, seats and headrests, or operating door locks and windows, or to release latches and etcetera.

Several devices are used, for example, for the deployment of air bags and anti–lock braking systems (ABS). In the modern cars are identified over 40 other automotive sensor applications, some of which could be addressed by the use of smart materials [2,8,12,15].

Some smart materials are being used in automatic light and heat control in the automotive industry (e.g. self–dimming mirrors and rear windows). A less mature application is the use of actuators as substitutes for small motors, the advantages here being reduced weight and fewer failures because of reduced complexity. Also less mature is the use of smart materials to reduce noise and vibration, resulting in enhanced comfort and safety benefits, especially for professional drivers.[2,4,24]

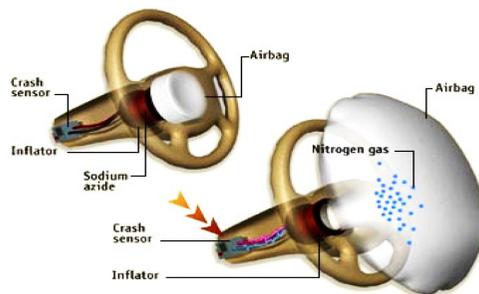


Figure 1. Example of sensor applications in air bagstechnology

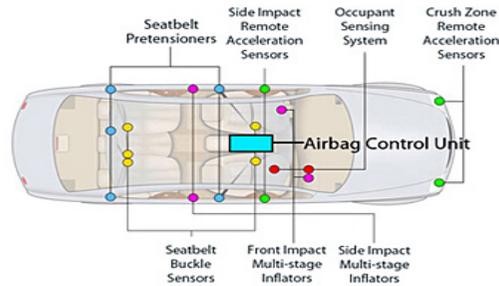


Figure 2. Example of sensor applications in anti-lock braking systems (ABS)

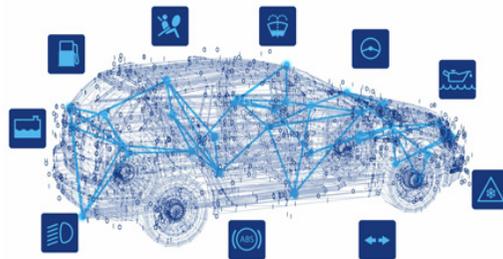


Figure 3. Automotive sensor applications

To replace conventional systems or introduce new capabilities into automobiles, systems based on smart materials and structures technology need to add functionality, performance and adaptability without decreasing reliability, while marginally increasing cost and weight.

Automotive applications tend to require high volume and high performance, the ability to function in a hostile environment and a low cost. Smart materials are likely to succeed in this sector if they can perform more than one function or if they can be integrated in a way that reduces assembly and production costs.

However, to advantageously exploit the capabilities of smart material-based sensors and actuators in vehicle technology requires multidisciplinary approaches to design and optimization, where improved controllability, maintainability and extendibility are key goals.

The innovative applications of smart materials in the automotive engineering includes but are not limited to [6, 24]:

- Smart material process and mechanism studies for automotive applications;
- Advanced vehicle control and multidisciplinary modeling to support the design of novel smart materials-based automotive components and/or systems;
- New designs and analyses of smart materials-based automotive components and/or systems for improving automotive performance, for example in reliability, safety, robustness and extendibility;
- Position/vibration/shock control of vehicles with smart materials-based components to improve driving comfort, handling stability and crashworthiness;
- Field testing and evaluation of practical automotive application systems featuring smart materials.

From an innovative materials engineering perspective, a passenger car is an aggregation of various control systems that interact with each other in complex ways. Each control system is made up of a plant, sensors, actuators and an electronic control unit (ECU), with many circuits which include passive components (such as resistors, capacitors, inductors) and integrated circuits (such as microcontrollers, communication gadgets). Some examples of automotive ECUs include:

- engine – controls engine performance and emissions;



- transmission – controls automatic transmission;
- electronic stability control – controls braking system;
- chassis – supports ride control system;
- instrument cluster – provides information to the driver;
- heating, ventilation, and air conditioning (HVAC) – controls climate inside the cabin;

Smart materials provide a choice to engineers because they offer new opportunities to reduce product complexity and weight of a car or automotive. Actuators and sensors made from smart materials also have the ability to improve vehicle performance and fuel economy, as well as enhancing convenience features [2,8,13,20,24].

Smart materials are materials that react to changes in the environment and consistently repeat recurring behavior. In the automotive sector, there have been some recent breakthroughs in using shape–memory alloys and piezo–ceramic materials which have numerous application opportunities [2,8,13].

Most of smart materials used in the automotive industry change their shape or structural properties on external stimuli like heat, magnetic field, electrical voltage or stress. The most preferred smart materials, like shape–alloy metals can “remember” their shapes and structures and revert to their original states once the external stimuli is removed [8,13,24,25].

The introduction of smart materials technology–based products consolidated the developments in the automotive sector. Important technical issues included enhanced actuator performance, device integration and cost–reduction [2,20,24,25].

Although the concept of Integrated Vehicle Management and its associated technologies can be complex in its implementation, it is essentially based upon a simple idea: the more you know about a particular machine’s ability to function, the quicker you can act to prevent malfunctioning. This rapidly developing area of engineering seeks to enable better management of both the vehicle and vehicle fleet health. Use of this concept can improve vehicle reliability, safety, and reduce unnecessary, unscheduled maintenance through the use of diagnostic and prognosis systems that monitor data and overall vehicle health [10,11,20,24,25].

As a result, the smart materials are used in several functional applications in the automotive industry [2,24,25]:

- passive sensors, for converting mechanical force or movement into an electrical signal, such as accelerometers, knock sensors, suspension load sensors, airbag impact sensors and intruder alarms etc.
- actuators, for converting electrical energy into mechanical displacement, such as valves for fuel injection systems, and devices for positioning headlamps and mirrors.

Automobile manufacturers and their components suppliers are working with the material scientists and applications engineers to develop new uses of smart materials to further enhance automobile safety, performance, energy–efficiency and comfort. The automotive industry continually implements technological innovations that make cars smarter, and therefore the smart sensors and actuators will play an increasingly important role, as the critical input/output devices for many automotive electronic systems.

Sensors are the key to life and survival – and to the success of modern technology. Nature has provided living creatures with a wealth of sensors for a light, sound, temperature, speed, motion, distance, force, pressure, acceleration, odor and so on – sensors, whose performance and specifications have often not been matched yet by man–made devices. Even at today's high level of electronics and information technology, sensors remain the crucial and decisive interface needed to reliably relate phenomena occurring in the environment to corresponding electric signals that can be processed to obtain the desired information and subsequent correct reaction of systems [9].

3. PIEZOELECTRIC CERAMIC COMPONENTS

Smart materials have one or more properties that can be dramatically altered, for example, viscosity, volume, conductivity. The property that can be altered influences the application of the smart material [9,18,19,24,25].



Smart materials include the piezoelectric materials. Some everyday items are already incorporating smart materials, and the number of applications for them is growing steadily.

Lead zirconate titanate ($\text{Pb}[\text{Zr}_x\text{Ti}_{1-x}]\text{O}_3$) – more commonly known as PZT, is the most common piezoelectric ceramic in use today. Currently, industrial and manufacturing is the largest application market for piezoelectric devices, followed by the automotive industry.

Many engineers are still learning about the piezoelectric effect or have little exposure to ceramic material advances. But when they're combined, ceramics and piezoelectric elements can lead to incredible improvements in component design and function.

When a piezoelectric material is deformed, it gives off a small electrical discharge. When an electric current is passed through it, it increases in size (up to a 4% change in volume). They are widely used as sensors in different environments. The piezoelectric effect describes the relation between a mechanical stress and an electrical voltage in solids. It is reversible: an applied mechanical stress will generate a voltage and an applied voltage will change the shape of the solid by a small amount. In physics, the piezoelectric effect can be described as the link between electrostatics and mechanics [9,18,19,24].

Piezoelectric ceramic components composed of PZT have enabled many recent technological innovations in the automobile industry. The PZT components can be found throughout many state-of-the-art vehicles, enhancing safety, performance, energy-efficiency and comfort.

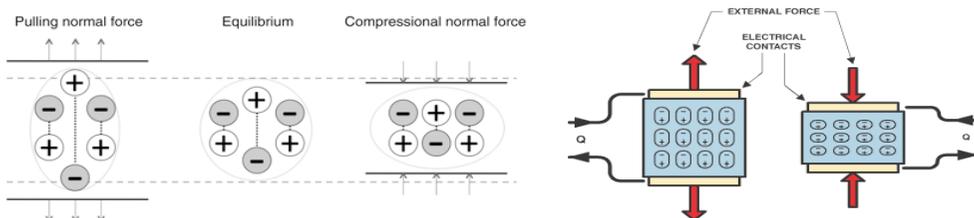


Figure 4. The piezoelectric concept and the piezoelectric effect

Piezoelectric sensors have proven to be versatile tools for the measurement of various processes. They are used for quality assurance, process control and for research and development in many industries. In the automotive industry, piezoelectric elements are used to monitor combustion when developing internal combustion engines. The sensors are either directly mounted into additional holes into the cylinder head or the spark/glow plug is equipped with a built-in miniature piezoelectric sensor.

PZT's attributes of producing an electrical charge when mechanically compressed or vibrating when an electrical charge is applied, make it very conducive for passive sensing, active transmitting and mechanical displacement applications. Piezoelectric materials are particularly useful for sensing applications due to its high sensitivity and permittivity. As such these piezoelectric ceramics are frequently used in low power applications as transducers, receivers and generators.

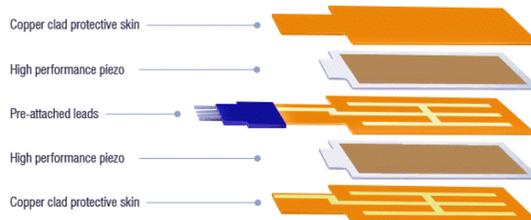


Figure 5. Piezoelectric sensors



The automotive industry utilizes different types of piezoelectric materials, each providing a set of unique properties suitable for a range of applications. The piezoelectric materials are a machineable ceramics and can be precision dimensioned into tubes, rings, discs, plates, and hemispheres, tailored to exacting customer specifications. The PZT material is also versatile from a forming aspect as it can be net shaped by pressing, extruding and casting into these same shapes as well as complex components including the multilayer actuators. Sizes range from microns to centimeters. Electrode choices are extensive including Silver, Nickel, vacuum deposited Nickel–Chrome, Gold, Tin, Aluminum and Vanadium [9,12,17–19].

Piezo–ceramic actuator and sensor design is based on customer specifications which generally include:

- the motion requirement (for actuators) or the voltage requirement (for sensors);
- the force requirement (for actuators) or the current requirement (for sensors);
- the response time;
- the operating frequency range;
- the space available for actuator;
- the voltage available;
- the stability;
- the temperature range.

The piezoelectric ceramic materials used for sensors (such as PZT ceramic) have a piezoelectric constant/sensitivity that is roughly two orders of magnitude higher than those of the natural single crystal materials and can be produced by inexpensive sintering processes. The piezo–effect in piezo–ceramics is „trained”, so their high sensitivity degrades over time. This degradation is highly correlated with increased temperature. Typical PZT characteristics include:

- wide range of frequencies in transmit and receive (sub–audible, audible, ultrasonic);
- high output, low drive material;
- high frequency, fast response time;
- high sensitivity for active or passive use;
- ability to use with low or high voltage drive circuits;
- good mechanical and acoustic coupling;
- wide variety of shapes and sizes that can be customized to meet specific requirements and applications;
- wide variety of compositions that can be selected to meet specific requirements and applications.

PZT–based materials are components of ultrasound transducers and other sensors and actuators, as well as high–value ceramic. PZT is also used in the manufacture of ceramic resonators for reference timing in electronic circuitry. Therefore, piezoelectric sensors are destined to:

- vibration, shock and acceleration measurements;
- acoustic measurements;
- pressure measurements;
- force and load measurements;
- torque measurements;
- other general topics;

These small and strong materials offer a wide frequency range, suiting a variety of applications and specific design needs without sacrificing performance. Typical PZT applications include the automotive industry, such as power seat controls, reversing/collision avoidance sensors, anti–knock sensors, intrusion alarms, vibration monitoring, flow and level sensors, computer hard drives, touchscreen displays, advanced acoustics and optical switching etc. For example, we will find PZT sensors under the hood detecting engine knocking, PZT transducers in the gas tank measuring the fuel level, PZT actuators operating valves in pneumatically adjustable driver’s seats, PZT ultrasonic transducers on the front, rear, and side of the car as parking sensors, and PZT generators in the wheels harvesting energy that powers tire pressure monitoring systems.



4. CONCLUSIONS

By definition, smart materials and smart structures – and by extension smart systems – consist of systems with sensors and actuators that are either embedded in or attached to the system to form an integral part of it. Smart materials are used in number of areas. The potential future benefits of smart materials, structures and systems are amazing in their scope. This technology gives promise of optimum responses to highly complex problem areas in the automotive industry, enhancing the survivability of the system and improving its life cycle. Moreover, enhancements to several products could provide better control by increasing the precision. Another possible benefit is enhanced preventative maintenance of systems and thus better performance of their functions.

One of the first attempts to use the smart materials technology involved materials constructed to do the work of electromechanical devices. Since then, many types of sensors and actuators have been developed to measure or excite a system. This technology is still in its infancy and the scientific community is just beginning to scratch the surface of its potential. It has been emphasized that materials especially the advanced materials are scientifically and technologically very important for the development of the automotive sectors.

By combining our active and passive technology with the innovative electronics and sensing capabilities, intelligent systems are created which help enhance the safety of pedestrians, drivers and passengers. The integrated technology warns the driver, actively assists to help avoid danger and intervenes to lessen the impact of an accident or helps to avoid one altogether. This integration is also key to the future of enhanced vehicle control, car-to-car, car-to-infrastructure and occupant/pedestrian protection developments.

Analyzing and reacting to the many sensor data inputs available on a vehicle's electronic communication network leads to systems that use active safety data to help ready passengers before a crash occurs and better mitigate the effects of the crash through active seat belt systems or pre-arming airbags. Using proprietary algorithms, these intelligent systems sense, calculate and adapt to help drivers avoid or mitigate an accident. Incorporating this advanced awareness yields a higher level of safety, efficiency, comfort and convenience.

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