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Review article

PROPERTIES OF SMART MATERIALS FOR MECHATRONIC APPLICATIONS

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Abstract

The standard of living and welfare of the people are closely related to the development and improvement of the performance of new engineering materials and devices. These new engineering materials have led to the emergence of new smart engineering devices and systems, such as mechatronic systems with high performance that are used in various industrial fields to reduce the cost of living and extend the quality of our everyday life services in all aspects. In recent years, smart materials have received a wide range of applications due to their unique properties when interacting with external stimuli in controlled conditions and manifest their functions according to the properties. The use of these unique properties of smart materials with the functional methodology of integration and interaction has influenced the emergence of mechatronics as a new technology that combines mechanical, electronics, computer, and information technologies. Mechatronics technology requires that these smart materials with certain properties change or adapt their behavior according to the controlled external condition, including temperature, stress, strain, light, pressure, moisture, pH, electric field, magnetic field, different types of radiation, etc.

This article aims to describe the properties of these intelligent materials, focusing the objective on the specific properties of piezoelectric materials, which nowadays play a major role in the so-called smart materials for application in mechatronics, using the available literature data as well as several years of authors' professional experience as professors in the field of engineering, materials science, and technology. Results from this article provide a summary of the main properties of piezoelectric materials used for application in mechatronics.

Keywords: smart materials, piezoelectric effect, remote actuation, structural changes, shape memory alloys.

1 Introduction

Nowadays, smart or intelligent materials have received a wide range of applications due to their unique properties when interacting with external stimuli in a controlled condition. The use of these unique properties with the functional methodology of integration and interaction has influenced the emergence of mechatronics as a new technology that combines mechanical, electronic, computer, and information technologies. Mechatronics technology requires these smart or intelligent materials with certain properties, to change or adapt their behavior according to the externally controlled condition, including temperature, stress, strain, light, pressure, electric field, magnetic field, moisture, pH value, different types of radiation, etc. (Maksuti & Ziberi, 2019).

This article aims to describe the basic properties of smart materials used for application in mechatronics, by reviewing and collecting the available literature sources as well as several years of authors' professional experience as professors of engineering, materials science, and technology. Literature sources include engineering handbooks on materials, published journals on engineering materials, databases for engineering materials as well as other sources.

The objective of this article is focused only on the specific properties of piezoelectric materials because as it is well known there are many types of smart materials that are used in mechatronics.

2 Literature review

2.1 *Definition of smart materials*

There are various definitions of the term smart materials in the literature. Also, different terms of such materials can be encountered in literature, such as intelligent materials, smart materials, adaptive materials, or even multifunctional materials (Ćwikła, 2013). In the beginning, smart or intelligent materials were defined as materials with a timely response to their environment, however, the definition of smart materials has been expanded to materials that receive, transmit or process a stimulus and respond by producing a useful effect which may include a signal that materials are acting upon it (Kamilla, 2013). According to (Takagi, 1990) smart or intelligent materials may be defined as materials that respond to environmental changes at the most optimum conditions and manifest their functions according to the properties. According to (Mishra, 2017) smart or intelligent materials may be defined as material that reacts to its environment independently, the reaction may exhibit itself as a change in volume, color, viscosity, odor and this may occur in response to a change in temperature, stress, electric current, pH value or magnetic field. According to (Bohidar, Kumar, Mishr, & Sharma, 2015) smart or intelligent materials are materials that have intrinsic and extrinsic capabilities, first, to respond to stimuli and environmental changes and, second, to activate their functions according to these changes. Also, the literature offers other definitions for intelligent materials such as smart or intelligent materials are materials that "remember" configurations and can convert to them when given a specific stimulus (Aher, Desarda, Shelke, & Chaudhari, 2015), smart or intelligent materials are those materials that can significantly change their thermal, optical, mechanical and electromagnetic properties in a controllable and predictable manner in response to their environment (Kumawat, et al., 2017), smart materials are materials, which possess the ability to change their physical properties in a specific manner in response to specific stimulus input (Hubballi, Harkude, & Jadav, 2018), smart engineering material is any innovative material which undergoes a macroscopic change in one of its physical-mechanical properties due to a non-mechanical external stimulus and that is capable of being controlled (Spaggiari, Castagnetti, Golinelli, Dragoni, & Mammano, 2016). Consequently, the term smart material is not very well defined and frequently used to describe different systems and systems behaviors (Aher, et al., 2015). Despite the rapid development of such materials, no single universal definition of intelligent materials has been developed. A smart or intelligent material is most frequently defined as the material which is capable of reacting to external stimuli by making significant changes in its properties to provide a desired and efficient reply to the stimulus (Ćwikła, 2013). According to (Kaushal & Rawat, 2016) smart or intelligent materials are defined as materials which have built-in or intrinsic sensors, actuators and control mechanisms whereby it is capable of sensing a stimulus, responding to it in a predetermined manner and extent, in a short/appropriate time, and reverting to its original state as soon as the stimulus is removed. Takagi (1990) defined smart materials as materials that respond to environmental changes at the most optimum conditions and manifest their functions according to the changes.
Figure 1 schematically presents the reaction of smart materials to the action of the external environment, thus showing their beneficial effect in use. Smart or intelligent materials are inspired by nature and try to mimic the adaptive characteristics of natural systems. Briefly, it is possible to say that smart materials have special properties that combine mechanical and non-mechanical fields, conferring adaptive characteristics (Savi & Steffen Jr, 2012).

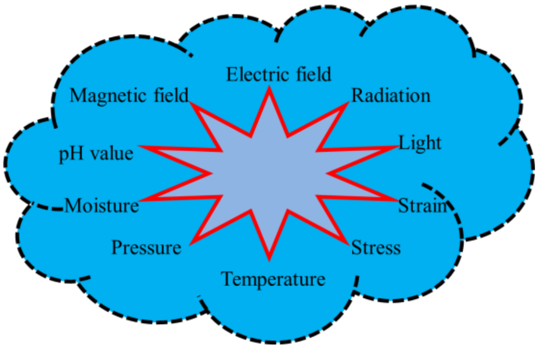

Figure 1. Reaction of smart materials to the action of the external environment

2.2 *Types of smart materials*

It is worth noted that according to their different behavior, different types of smart or intelligent materials are available in the literature. There are many types of smart materials, and there is still a lot of research being done in the field of these materials, but the objective of this article is focused only on the specific properties of piezoelectric materials that are mostly used in mechatronics technology.

According to (Kaushal & Rawat, 2016; Damodharan, Sreedharan, & Ramalingam, 2018; Sadiku, Tembely, & Musa, 2017) a smart material can be active or passive, figure 2. Active smart materials can modify their geometric or material properties under the application of electric, thermal or magnetic fields, thereby acquiring an inherent capacity to transducer energy. Piezoelectric materials, shape memory alloys, electro rheological fluids, and magnetostrictive materials are considered to be the active smart materials and therefore, they can be used as force transducers and actuators. On the other hand, the materials which are not active are called passive smart materials (Kamilla, 2013). According to (Kaushal & Rawat, 2016) passive smart materials are the materials that are inactive to the response. Fiber optic material is a good example of passive smart material. Such materials can act as sensors but not as actuators or transducers (Kamilla, 2013). This classification of smart materials is not standard classification, therefore different classifications of smart materials are used in the academic, scientific, or industrial community (Aher, et al., 2015). From the reviewed literature it can be seen that smart piezoelectric materials, memory shape alloys, magnetostrictive materials are mainly used in mechatronic systems including manufacturing technology and engineering. It is worth mentioning that in other fields different mechatronic systems are used, but in this case, they are produced from other smart materials, which as mentioned above are in a wide spectrum. In recent years, smart materials have proved to represent an effective way for developing a new generation of miniaturized electromechanical transducers. Thanks to their many features such as high energy density and efficiency, low power requirement, low cost, scalability, and high compactness, smart materials can help to improve the performance of several mechatronic systems, ranging from industrial to non-industrial applications (Rizzello, Riccardi, Naso, Turchiano, & Seelecke, 2017).

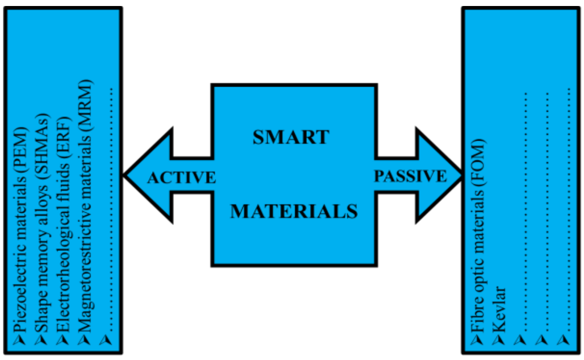

Figure 2. Types of smart materials

2.3 *Properties of smart materials used in mechatronics*

To meet specific requirements and to use them efficiently and effectively in general and in mechatronic applications in particular, smart materials must meet certain properties (Aher, et al., 2015), such as:

-mechanical properties, including yield strength (Re), ultimate tensile strength (Rm), the module of elasticity (E), hardness (H) such as plastic behavioral in use, etc.,

-physical properties including lightweight density, superconductivity, thermal conductivity, electric/electronic conductivity,

-technological properties, including the ability of processing with all technological processes,

-environmental criteria, including environmental protection and recycling ability,

-production cost,

-sustainable criteria, etc.

By changing their properties, smart materials provide numerous possible applications and therefore are useful as a constitutive part of mechatronic systems. So, with interaction and adaptation with external stimuli, these materials change their physical and mechanical properties and hence perform useful and usually repetitive actions that manifest macro effects, which are attributes of mechatronic systems. The other properties mentioned above, such as technological properties, environmental properties, production cost, sustainable criteria, etc., are also important and refer to the aspect of production and commercialization of these materials.

2.4 *Smart materials for application in mechatronics*

Smart or intelligent materials form a group of new and state-of-the-art materials now being developed that will have a significant and wide range of applications due to their varied response to external stimuli (Hubballi, et al., 2018). Smart materials are usually used to develop sensors and actuators (effectors) and these components in combination with a control mechanism (processors) form the mechatronic system, or smart system, figure 3, whose integral function is important and attractive in many practical applications. Smart materials are usually attached or embedded into structural systems to enable these structures to sense, process the information and evoke reaction at the actuators. Thus, smart materials respond to environmental stimuli and for that reason are also called responsive materials (Varadan, Vinoy, & Gopalakrishnan, 2006). It is worth mentioning here that the integration of these components, technically and technologically is more advanced and requires multidisciplinary and interdisciplinary knowledge. Smart materials in mechatronic systems are usually utilized as actuators and sensors, and their associated "stimulus" and "response" are attached with the processing/control unit, as shown in figure 3. The selection of sensors may be based on the type of stimuli expected, the processing/control unit may consist of information processing and storage units, while the actuator may depend on the type of function expected from the system. (Varadan, et al., 2006).

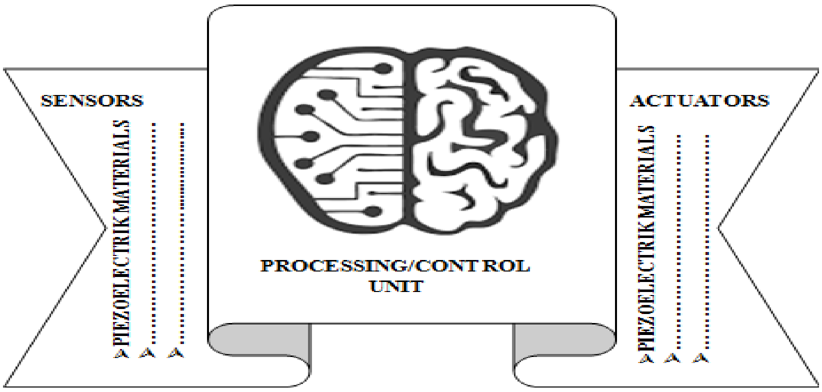

Figure 3. A typical mechatronic system

As figure 3 shows, smart materials sense changes from the external surrounding environment, process the sensed data through the processing/control unit and finally execute the activity by the actuator. Mechatronic systems that can be attached and adapted from these smart materials to provide a useful effect by changing their properties can also be called smart systems. Mechatronic systems or smart systems integrate the properties of sensors, actuators, and processing/control mechanisms to respond to a given stimulus in a functionally useful manner. The use of beneficial effects of these mechatronic systems is still in its early stages of development and the scientific community in this field continues to explore its beneficial potential in our daily lives. Mechatronic or smart systems containing sensors, processing/control mechanisms and actuators capable of sensing, controlling, processing, and activating an action is analogous to the body's biological system, figure 4.

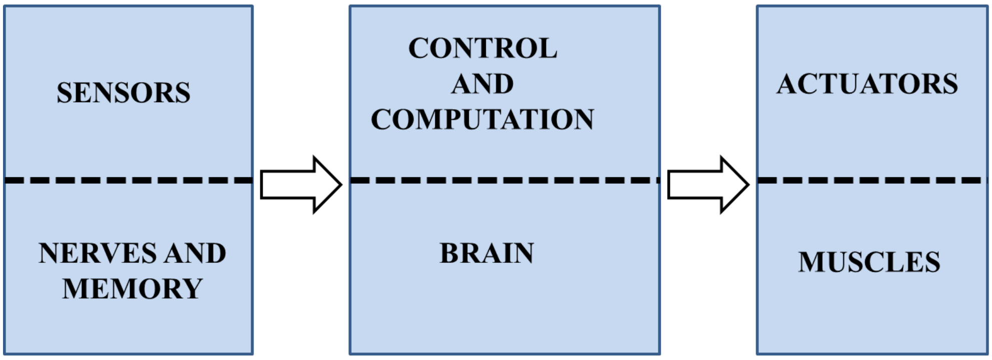

Figure 4. Mechatronic system versus biological body system

Mechatronic systems incorporated with others engineering systems lead to increased flexibility and performance of these integrated systems operating in various new or existing applications, in the field of science, engineering, and technology. Smart materials are the materials of the future in science, engineering, and technology, with a wide range of applications in mechatronic systems. Current efforts in the world of smart systems aim to reduce their overall size, namely the production of smart micro-electro-mechanical systems (MEMS). The application of smart materials in mechatronic systems and the integration of these systems with other engineering systems create more functional and smarter devices that are used in everyday life in various applications, such as automobiles, rail transport, medicine, aerospace, marine, etc. It is worth mentioning that smart materials incorporated in mechatronic systems cover all areas of science and engineering. The key to a competitive advantage of the 21st century will be the development of products with increased levels of functionality. Smart materials will play a critical role in this development (Davies; Filetin, 2017).

2.4.1 Piezoelectric materials for mechatronic applications

Piezoelectricity derives its name from the Greek word "πιεζειν = *piezein*" which means, to squeeze or press, and the distinguishing feature of piezoelectric materials is the inherent ability to convert mechanical energy into electrical energy and vice versa (Peters, 2013) figure 5.

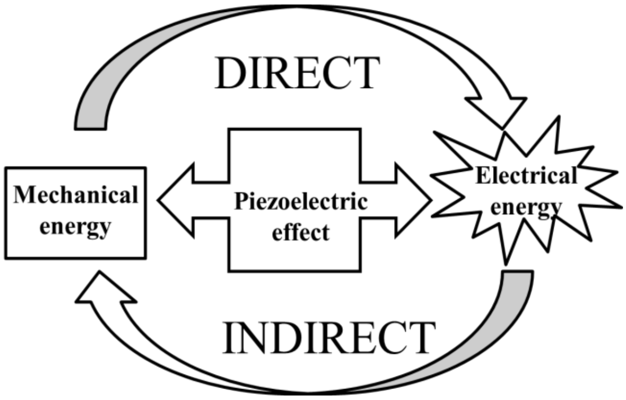

Figure 5. Piezoelectric effect of smart materials

The direct effect, i.e. the conversion of mechanical energy into electrical energy which is typical for sensor applications (e.g. force and acceleration sensors), figure 6(a) and indirect or inverse piezoelectric effect, i.e. the mechanical excitation by application of an electric field (actuator applications, e.g. ultrasound generation, stack actuators), figure 6(b). The piezoelectric effects are mainly used for piezoelectric sensors and piezoelectric actuators, which are used in micro-electro-mechanical systems (MEMS). In 1880, Pierre and Jacques Curie published the first experimental demonstration of a connection between macroscopic piezoelectric phenomena and crystallographic structure (Ghareeb & Farhat, 2018).

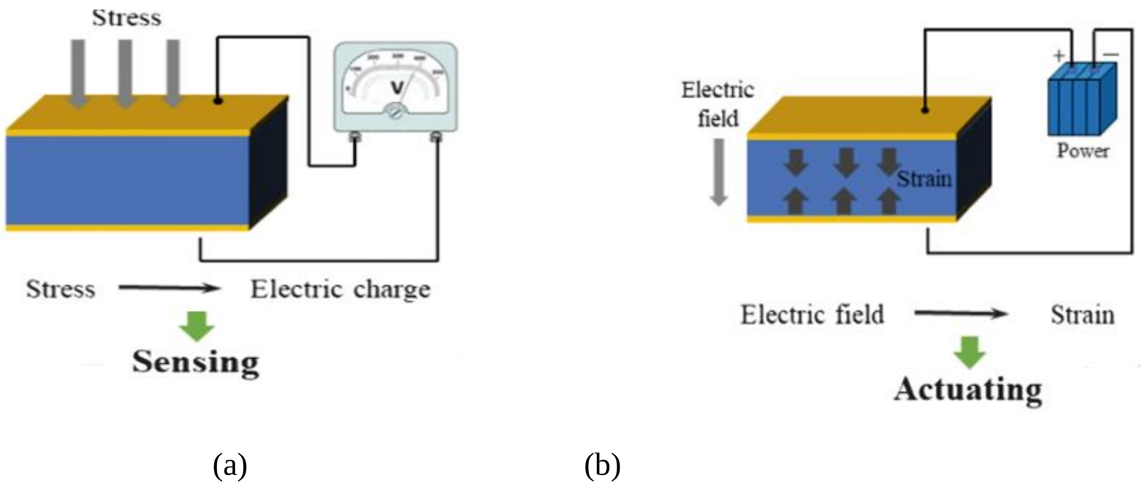

Figure 6. Piezoelectric effects: a- the direct piezoelectric effect, b- the indirect (reverse) piezoelectric effect
Source: Rödel, J., & Li, J.-F. (2018). Lead-free piezoceramics: Status and Perspectives. *MRS Bulletin, 43*(8), 576-580

For this reason, there are different types of piezoelectric materials used to meet that demand. The most commonly used piezoelectric materials can be placed in two main groups: single crystals and polycrystalline ceramics. Some popular crystals include quartz (SiO_2) and lithium tantalite ($LiTaO_3$), while popular ceramics are barium titanate ($BaTiO_3$) and lead zirconate titanate (PZT). There are many other types of piezoelectric materials which include zinc oxide (ZnO), aluminum nitride (AlN), polyvinylidene fluoride (PVDF), and cadmium sulfide (CdS) (Johnson, 2011).

Piezoelectric materials are smart materials that have found increased application in mechatronics as active or passive components. As a result, these materials can be used to convert mechanical energy to electrical and vice versa. This phenomenon provides a unique mechanism for remote actuation, attracting a lot of attention to the research of piezoelectric materials as smart and functional materials. These materials have a very important role and wide application in modern industries in a variety of mechatronic systems. Recently, piezoelectric materials are recognized as promising and high-performance materials in the field of micro-electro-mechanical systems (MEMS) (Kumar & Lakshmi, 2013).

3 Conclusions

By reviewing the available literature, the following conclusions can be drawn:

-The literature review showed that smart materials are widely used in mechatronics and promise even greater use in the future.

-The future development of new smart materials with better performance and capabilities will significantly improve the comfort of our society through the execution of useful selective and usually repetitive functions by changing their properties in interaction with the surrounding environment, integrated into mechatronic systems.

-Piezoelectric materials are the most common type of smart materials that are used for mechatronic applications and thanks to the unique piezoelectric effect, they are expected to be used even more in mechatronic applications in the future, as sensors or actuators integrated with the processor/control units.

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