Review Article

Review of Smart Metallic Materials Classification

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Received: 03 June 2023 - Accepted: 24 October 2023

Abstract

Along with material science progress, many new high-quality and cost-effective engineering materials have been introduced in various fields. Smart materials are the new generation of materials superior to construction and commonly used materials. With their inherent intelligence, these materials can adapt to external stimuli such as loads or the environment. Smart materials refer to those materials that understand and react to their environment and surrounding conditions. The crystal structure of these materials responds to applied force (mechanical, electrical, magnetic, etc.). According to NASA's definition, smart materials remember positions and can return to them with certain stimuli. Smart materials are used in systems whose inherent properties can be changed to achieve the required performance. In this article, while introducing the application and development of memory metal smart materials, the relationship between the development of advancing technologies and the development and application of this class of material is discussed.

Keywords: Shape Memory Alloys, Piezoelectric Materials, Chromic Materials.

1. Introduction

Most of the technologies are based on engineering materials. One of these technologies is artificial intelligence and its application in various industries. We need hardware and software tools with high processing capabilities to improve the quality and effectiveness of artificial intelligence. Therefore, more advanced engineering materials are required to increase processing efficiency, which are known today as smart materials. Engineering materials are divided into four main groups: metals, ceramics, polymers, and advanced materials [1]. In the meantime, advanced engineering materials are more interesting due to their diverse technological applications. Advanced materials cover various applications, including computer semiconductors and electronic chips and vacuum tubes [2].

Today, the need to use smart materials in various industries is due to the ability to change their properties in the face of external stimuli. In addition, they adapt in response to environmental conditions [3]. This material is reversible to its original properties when the external stimulus is removed. Factors such as temperature, mechanical stress, strain, magnetic field, electric current, pH, or chemical effect can change these materials' size, color, moisture, and fluidity [4]. Therefore, applications of smart materials such as sensing capability [5], stimulation [6], and drug delivery [7] can be achieved using the indicators mentioned above.

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In addition, smart materials have characteristics that distinguish them from other materials, such as [8]:

• They respond to different stimuli,
• Respond to external influences without wasting time,
• They have self-actuation or inner intelligence.
• Their responses to environmental stimuli are distinct and predictable,
• Both stimulus and response processes occur in the same matter area.

2. Types of Smart Materials

According to different responses to environmental stimuli, smart materials are classified into several types below [8].

• Shape memory alloys (response to heat and stress),
• Piezoelectric materials (response to electricity and stress),
• Magnetoelastic material (response to magnetic field),
• Electrostrictive materials (response to an electric field),
Chromic materials (respond to different stimuli),
• pH-sensitive substances (response to physical, chemical, or biological stimuli),
• Electrorheological fluid (response to an electric field)
• Magnetic fluids (response to a magnetic field).

2.1. Shape Memory Alloys

Shape memory alloys are smart materials with at least two main phases. They can be transformed from one phase to another by changing the temperature or applying stress. These materials can

remember their shape at the beginning (austenite stage), and after changing shape (martensite structure), they can recover their original shape. During the phase transformation, the atomic structure and microstructure of the shape memory alloy change, called shape memory transformation [9]. By removing the external stimulus, these materials are reversible to their original state.
Researchers have investigated the effect of many parameters, including adding new elements to binary shape memory alloys [11, 10], heat treatment [12], mechanical treatment [13], different cooling methods [14], and surface optimization. The physical properties of shape memory alloys have been investigated using materials [15] and other techniques for sample preparation [16]. This type of smart material can have several features, such as thermoelasticity (reversible transformation of austenite to martensite with increasing and decreasing temperature) [17], superelasticity (increasing and decreasing strain during the reversible transformation of austenite and martensite), and impactability or absorption (conversion of vibrational energy, such as impact or sound wave energy, into internal energy) [18].

2.2. Piezoelectric Materials

If piezoelectric materials are subjected to external mechanical stress, an electric potential difference is produced, and they can change their size. Energy can be released mechanically. This process is reversible and can be found in materials with the ability to contact electricity (electricity production by the friction process) or materials with the ability to pyroelectricity (production of electricity with heat). When the bias voltage is applied perpendicularly to the polarity of the piezoelectric material, the bending pattern and bending direction depend on the orientation of the material. The first piezoelectric actuators were made of lead-zirconate-titanate. These actuators can move the tool with precision of up to one nanometer. Another type is piezo-tube actuators that create radial and axial movement [19]. Characteristics that make them superior to others, such as being insulated from electric and magnetic fields or electromagnetic radiation. They also work in a wide range of temperatures [20], having high sensitivity [21], possibility of use in various applications and efficiency at high frequencies [22]. Piezo sensors convert mechanical energy into electrical power. Therefore, they can be classified as a type of generator [23].
Inorganic and organic materials are piezoelectric. The dentin of teeth and bones is organic materials with two mineral substances forming collagen protein and hydroxyapatite [24]. In addition, some ceramic minerals such as zinc oxide, aluminum nitride [25], lead-zinc-zirconite-titanium oxides with the composition of $Pb(Zn, Al)O_3$ and quartz with the chemical composition of SiO_2 [26] can have piezoelectric properties.

2.3. Magnetoelastic Materials and Electrostrictive Materials

Electric circuits are the main components of detectors and measuring instruments. In the same way, piezoelectric materials can directly measure mechanical quantities such as torque, acoustic sound, acceleration, force, and tension. These materials have many Magnetoelasticity is a phenomenon in which the length or dimensions of a ferromagnetic material change with the application of a magnetic field (Joule effect). These materials can be classified as positive or negative magnetoelastic materials. They can be stretched or contracted in response to magnetic fields.
The response of electrostrictive materials to an electric field is done by changing their size. When electrostrictive materials are exposed to an electric field, the ions are displaced from their original position, increasing their size. By the way, piezoelectric materials also show this feature; however, there are many differences between them [27].

2.4. Chromic Materials

Chromic materials change their color in response to environmental conditions. They can return to their original color after the effect disappears. In the following, different groups of chromic materials are described.
Photochromic: This group of chromic materials is sensitive to visible and ultraviolet radiation. It can provide colors that depend on the intensity of the specific radiation range. Photochromic materials can be found in organic or inorganic form. When exposed to sunlight, photochromic glasses reduce transparency and brightness. In addition, photochromic materials are also used in textiles and military protective clothing [28].
Thermochromic: Increasing the temperature beyond the critical level leads to thermochromic materials' color change. They can be produced from semiconductors, metals, and liquid crystals. Temperature can change the crystal structure and spatial position of atoms or rearrange atoms in molecules without changing the substance's chemical composition. These types of materials are widely used in various fields. For example, thermometer strips can be used as temperature indicators, especially for body temperature.
Electrochromic: These materials can be transparent and reflective [29]. Their chemical composition responds to voltage. In some special polymers, the electrochromic effect is caused by metal oxide transfer [30]. Also, minerals can show electrochromic behavior by separating protons and electrons.

There are many applications based on the electrochromic effect. For example, electrochromic glass transparency decreases by applying voltage to it. Electrochromic windows have been used in Boeing Dreamliner 787, the high-speed train ICE-3 [31], electrochromic-based display devices [30], and replaceable car mirrors [32].

Magnetochromic: Magnetic fields can change the color of magnetic chromium materials. Ferrofluids are one of these materials containing magnetic particles in the range of 5-10 nm. When a magnetic field is applied, the particles are regularly aligned, so radiation rays are scattered from different semi-parallel planes containing suspended particles [33].

Piezochromic: Some materials can change physical properties such as absorption, emission, reflectivity, or transparency by applying a certain pressure and through bathochromic displacement. The compound $CuMoO_4$ requires 2.5 kbar to transform its color from green to red, while palladium needs more than 1.4 GPa. Piezochromic materials require very high pressure to change color. Therefore, they cannot be used as color pressure sensors. However, some polymers show bathochromic changes by applying only eight kbar [34].

2.5. pH-Sensitive Materials

Smart materials respond to physical, chemical, and/or biological stimuli. PH-sensitive polymers are one of the most significant families of smart materials that change color in response to a specific pH change. These substances can be acidic or basic and react with their opposite substances. Today, they are used in various fields, such as medicine for drug delivery, improving surface quality, or as a filter [35]. Halochromic materials are one of the highest pH-sensitive materials used in environmental sensors. They change their color through chemical bonding between hydrogen ions and hydroxides. For example, halochromic materials are employed in dressing and determining burn areas. These smart fabric bandages can change the skin's pH during healing and are effective for controlling skin healing [30].

2.6. Electrorheological and Magnetorheological Fluids

Fluids are classified into two categories: Newtonian and non-Newtonian fluids. Newtonian fluids have a linear relationship between their resistance to viscosity and the speed of the body penetrating them. Non-Newtonian fluids show different characteristics. For example, Oobleck is made from corn starch and water. Fast-sinking objects significantly change the viscosity of this material [36]. Magnetic fluids are non-Newtonian viscoelastic fluids with suspended iron particles and can change their viscosity and thickness under an external magnetic field. They contain microparticles ranging from 0.1 to 10 microns and larger than nanoparticles in Ferro fluids. Therefore, Brownian motion is less effective in these materials. Magnetic fluids can protect buildings from earthquakes [37].

Also, using Newtonian fluids in car shock absorbers reduces oscillations in the car's interior.

Similarly, an electrorheological fluid is a non-Newtonian viscoelastic fluid with irregular suspended particles like a magnetic fluid. When an electric field is applied to an electrorheological fluid, suspended particles stick together and create chains in the same direction as the electric field is applied. Electrorheological fluids, like magnetic fluids, can be used in similar intelligent application systems [38].

3. Smart Materials Applications

3.1. Engines and Cars

Piezomotor actuators are motors made with different piezoelectric materials and used for longitudinal and transverse movement. Each motor has four bases, and the bases consist of two parts. The upper part is designed to stretch the legs, and the lower part (the soles of the feet) is designed to bend forward and backward [6]. Fig. (1). shows how they work.

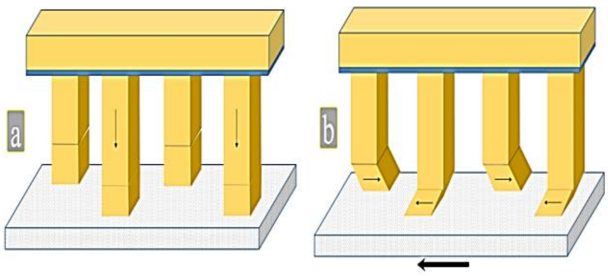

Fig. 1. Piezomotor actuators working: (a) Two actuator legs are drawn towards the plane, (b) then, the legs of the two actuator legs are bent in the opposite direction to each other [6].

At first, the longitudinal piezo motor is stretched axially. Then, a vertical voltage is applied to the legs to bend them. After that, two bent legs in the plane change position and turn to the opposite side. Then, these two legs are contracted while the other two legs continue the process. Since piezoelectric actuators can be controlled at nanometer levels, they are incorporated into most precision microscopes and ultra-small robots. Furthermore, the tracking accuracy is less than 5 nm for constant velocities (100 nm/s to 1 μm/s) and less than 400 nm for speeds greater than two mm/s.[6]

Linear magnetoelastic actuators consist of a circular cylindrical coil wrapped around a metal rod core. The magnetic field is created by applying direct current, which expands the metal core. Hence, the metal core movement can be used for various mechanical purposes (Fig. 2).

In addition, magnetoelastic actuators have been used in many other applications, such as sonar transducers, wireless rotary motors, electrohydraulic actuators, wireless linear micromotors, thin film applications in valves, and non-contact torque sensors [39].

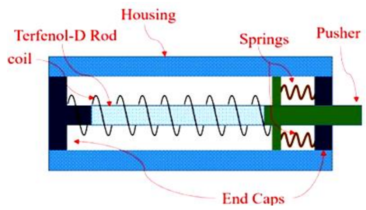

Fig. 2. Linear magnetoelastic actuator [39].

3.2. Aerospace

The fuel probe is an accurate ultrasonic indicator. Electric actuators make it. When the liquid fuel surface reflects the radiation wave, it is detected by a piezoelectric transducer, and thus, the fuel level can be accurately measured [40].
Another example are wings based on shape memory alloys or smart wings. This technology uses shape memory to change the wings' shape during takeoff and landing.
Therefore, hydraulic motor systems will be unnecessary. Also, the wings are raised and reduce noise production [41].

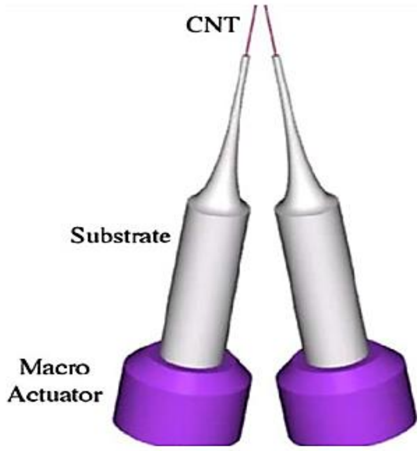

Fig. 3. Schematic diagram of Carbon nanotube based actuator [44].

3.3. Textile Industry

Memory polymers can increase the quality of smart clothing. Smart clothes can show one or more features, such as self-movement, self-cleaning, color change, or shape change. Since polymers change softness after the glass transition temperature, they can be used to produce clothing for ventilation and body temperature regulation.
Polymer clothes are waterproof. They can be designed to have minimal volume at ambient temperatures. Therefore, clothing prevents moisture penetration from the environment into the body or evaporation from the body into another domain. But at a temperature higher than the glass transition temperature, the molecules expand and, as a result, create small holes for ventilation [42].

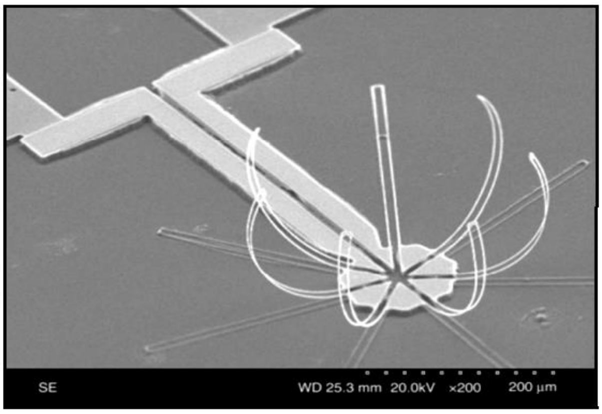

Fig. 4.TiNi/DLC microcage with TWSME [43].

3.4. Nanotechnology

3D carbon nanotubes have electromechanical characteristics suitable for actuators [44]. Optical nanotweezers have arms made of three-dimensional carbon nanotubes, which capture small objects in modern microscopes with high precision. The arms of optical nanotweezers bend elastically by applying voltage, and when the bias voltage becomes zero, they return to their original shape (Fig. 3).
In addition, the nanotube's diameter can be closely related to the elasticity of three-dimensional carbon nanotubes [45]. This technology allows users of scanning microscopes to perform electrical measurements and guide the sample using these arms. TWSME produces TiNi/DLC micro-cages (Fig. 4). This tool can perform the opening or closing process by using thermal or electrical energy.

3.5. Medicine

Smart materials in this field have many applications, as mentioned below.
Orthodontic archwires: First, gold alloys, stainless steel, beta-titanium, and Cr-Co-Ni alloys were used. Today, Ni-Ti alloys have quasi-elastic properties and have a longer life and medium strength with relatively high elastic recovery [46].
Bone plates: Some plates are made of shape memory alloys that glue broken body parts together (Fig. 5). These plates can store potential energy during deformation, so they can generate the appropriate force for broken bones and help us to weld them quickly [47].
Spine intervertebral implants: Memory alloys in the shape of a washer, called a vertebral spacer disc,

protect friction between the spine vertebrae (Fig. 6). These discs can withstand large deformations without restricting body movement. In the same way, the superelasticity of discs made of shape memory alloys can be used to save energy from elastic deformation and martensitic transformation. Therefore, releasing this energy can force the body to return to its original form [48].

Colonoscopy robots: A small worm-shaped robot based on shape memory alloy actuators. Fig. (7). shows a schematic diagram of a worm-like robot 95 mm long and 15 mm wide. When this robot passes through the large intestine, it can be easily monitored and elongated by expanding the shape memory alloy actuators [49].

3.6. Automobile Manufacturing

Electrochromic mirrors: One of the problems of driving at night is the reflection of the rear cars' light from the mirrors. To solve this problem, smart mirrors have been designed to reduce reflected light slightly. These mirrors are usually made of seven thin layers, including transparent glass, two transparent electrodes (anode and cathode), an ion storage layer, an electrolyte, an electrochromic layer (such as WO_3), and a normal glass layer.

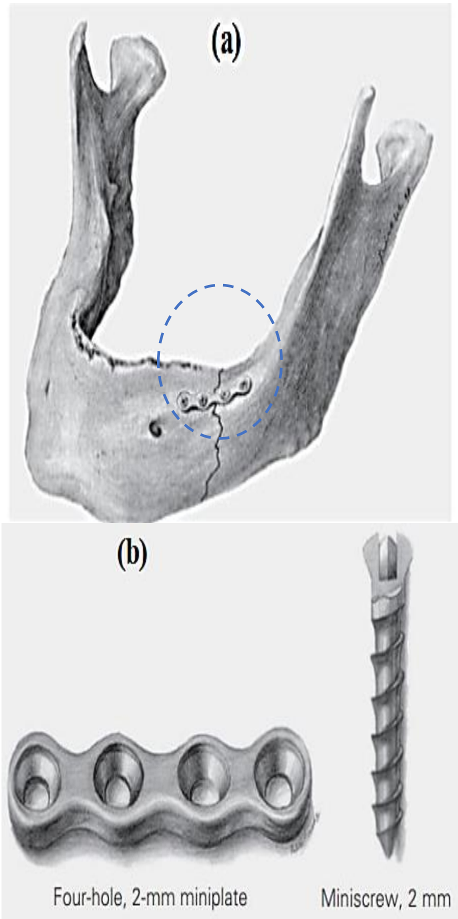

Fig. 5. plate made of shape memory alloy with several related screws [47].

Under normal conditions, the electrical circuit is opened, and almost all radiant light can be reflected from the mirror. Electric fields are created between the electrodes when the circuit is closed. Therefore, the electrons of the ion storage layer pass through the electrolyte layer and reach the electrochromic layer. As a result, the mirror becomes dark or cloudy, and accordingly, the reflected light decreases with the increase in electric potential difference [50].

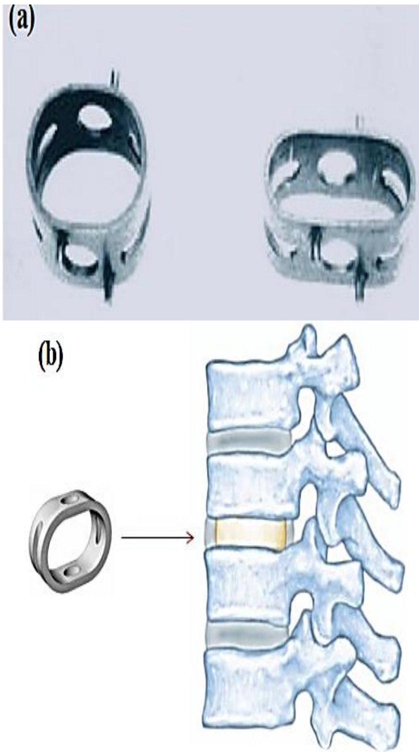

Fig. 6. (a) Spinal vertebral implants in austenite (left) and twinned martensite (right), (b) artificial disc made of shape memory alloy instead of the damaged disc [48].

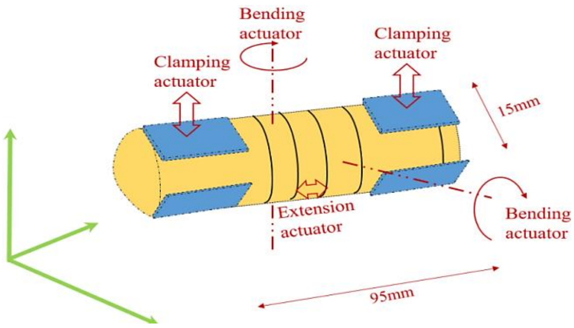

Fig. 7. Inchworm-shaped robot with three degrees of freedom to move [49].

Magnetic bumper: Magnetic shock absorbers damper systems include springs and shock absorbers. Shock absorbers are usually made of oil fluid in a closed cylinder and a moving piston (Fig. 8.a). A piston divides the fluid inside the cylinder into upper and lower chambers. Therefore, the fluid's viscosity can reduce the piston's speed when it moves up and down. Fig. (8.b) shows a bumper using smart magnetic fluid instead of normal fluid. There is also a built-in coil that can be controlled by electric current. When the intelligent magnetic fluid passes through the cylinder channel, it is affected by magnetic flux and can reduce momentum [51].

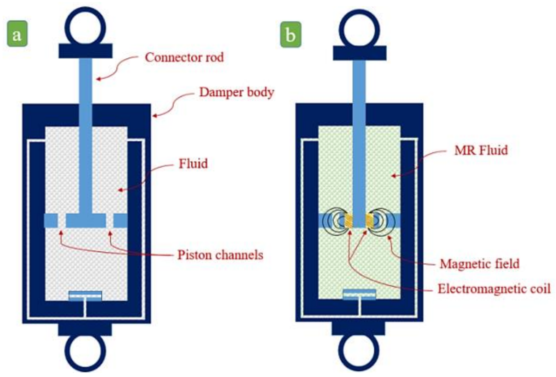

Fig. 8. shock absorber (a) with a conventional fluid, (b) with MRF that is restricted inside piston channels when magnetic field is applied.

4. Conclusion

Smart materials are vital in various fields such as medicine, automobiles, and robotics. Piezoelectric and shape memory materials are more widely used than other types, especially for actuating purposes. Some advantages include compatibility with the environment, high sensitivity to stimuli, and quick response to different conditions, relatively small size, and optimal energy consumption. Some of their limitations include the relatively high cost of preparation, inefficiency at all temperatures, increased sensitivity to chemical composition, and reduced efficiency due to fatigue or environmental corrosion.

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