INTRODUCTION TO SMART MATERIAL (OE-3)

(ME0221)

UNIT-1

INTRODUCTION

Characteristics of metals, polymers and ceramics:

Metals

- This type of materials has characteristics like, high electrical and thermal conductivity, the ability to be deformed or cut into new shapes without breaking, and high mechanical strength. Since metals must be reduced from chemical compounds, they tend to be somewhat more costly than non-metallic materials, and they are often vulnerable to corrosion damage as the metals react with their environment to re-form those compounds. They tend to be shiny and malleable. Metals have these characteristics because they have nonlocalized electrons.

Ceramics

- Ceramics are generally compounding between metallic and non-metallic elements and include such compounds as oxides, nitrides, and carbides. Typically, they are insulating (not electrical or thermally conductive) and resistant to high temperatures and harsh environments (corrosion resistant). They usually have lower electrical and thermal conductivity, higher stiffness, good resistance to corrosive environments, and lower fracture toughness than metals. With the exception of glasses, ceramics usually cannot be reshaped easily. To shape a ceramic, a mixture of ceramic powders, water, and binder materials is moulded into the desired dimensions to form a temporary shape. These temporary shapes called "green bodies" are then dried to remove water and heated to allow the binder materials to oxidize, leaving the ceramic powder particles to bond to each other during the high temperature baking.

Polymers

- Plastics (or polymers) are generally organic compounds based upon carbon and hydrogen. They are very large molecular structures. Usually, they are low density and are not stable at high temperatures. They can be readily formed into complex shapes. Their strength, stiffness, and melting temperatures are generally much lower than those of metals and ceramics. Their light weight, low cost, and ease of forming make them the preferred material for many engineering applications.

Composites

- A combination of two or more materials differing in form or composition. The different parts still have the same features they originally did, that is, they do not dissolve or merge completely into one another, however, their properties are enhanced by each other. Normally, the components can be physically identified and exhibit an interface (boundary) between one another. Fiberglass, a combination of glass and a polymer, is an example. Concrete and plywood are other familiar composites. Many new combinations include ceramic fibres in metal or polymer matrix.

Introduction to smart materials:

Introduction

- Smart systems consist of sensors and actuators that are either embedded in or attached to the system containing central control and command unit to form an integral part of it.
- Smart or intelligent materials are materials that have the intrinsic and extrinsic capabilities, first, to respond to stimuli and environmental changes and, second, to activate their functions according to these changes.
- Stimulus —stress, strain, light, electric field, temperature and pressure, etc.
- Response —motion or change in optical properties, modulus, surface tension, piezoelectricity etc.

Classification of smart materials

Actively Smart:

They possess the capacity to modify their geometric or material properties under the application of electric, thermal or magnetic fields, thereby acquiring an inherent capacity to transduce energy.

- Piezoelectric
- Magneto strictive
- Shape memory alloys
- Electro-Rheological fluid, etc.

They can be used as force transducers and actuators

Passively Smart:

Those smart materials that are not active are called passively smart materials. Although smart, they lack the inherent capability to transduce energy.

- Optic fibers

These materials can act as sensors but not as actuators or transducers.

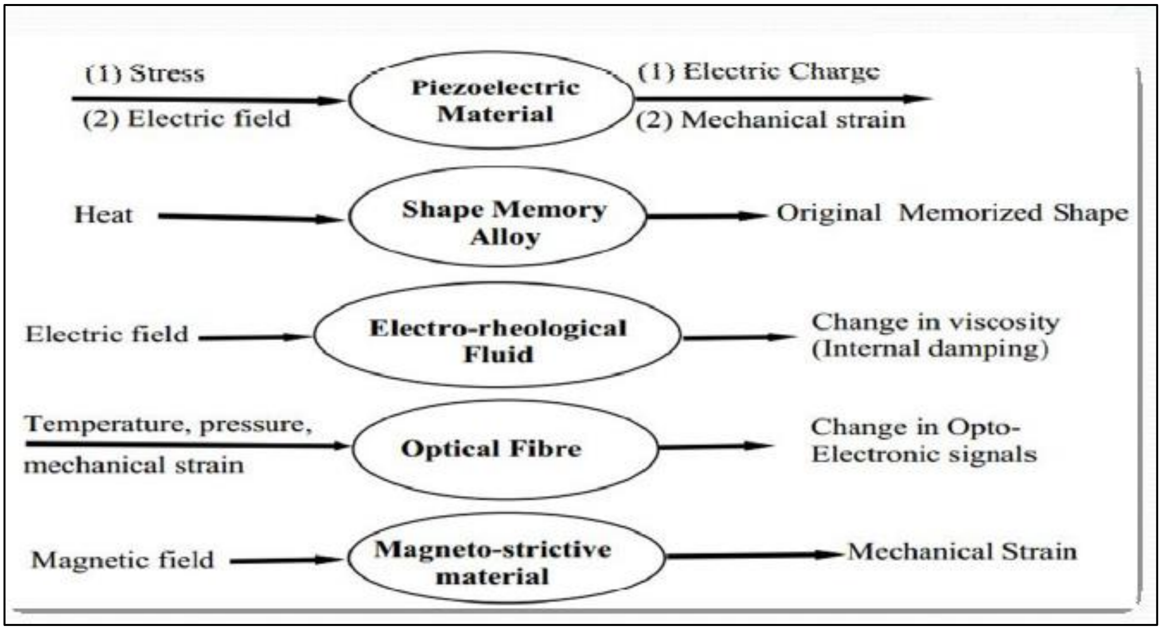


Fig: Common smart materials and associated stimulus response

Smart Technologies Prospects*:

- New sensing materials and devices.
- New actuation materials and devices.
- New control devices and techniques.

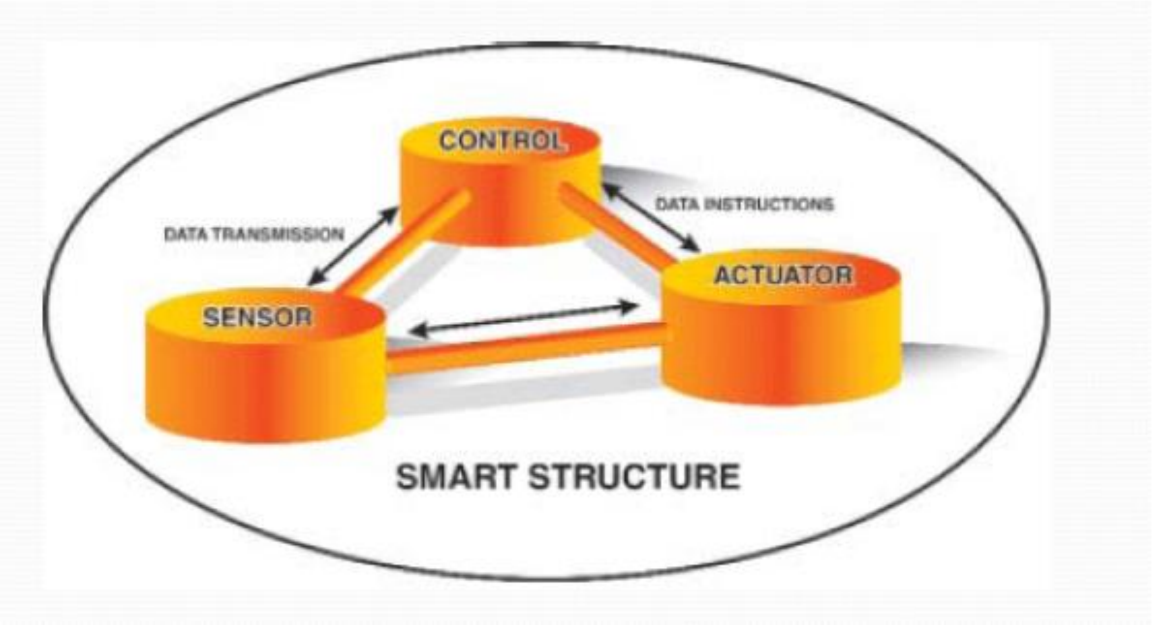
Self-detection, self-diagnostic, self-corrective and Self-controlled functions of smart materials/ systems.

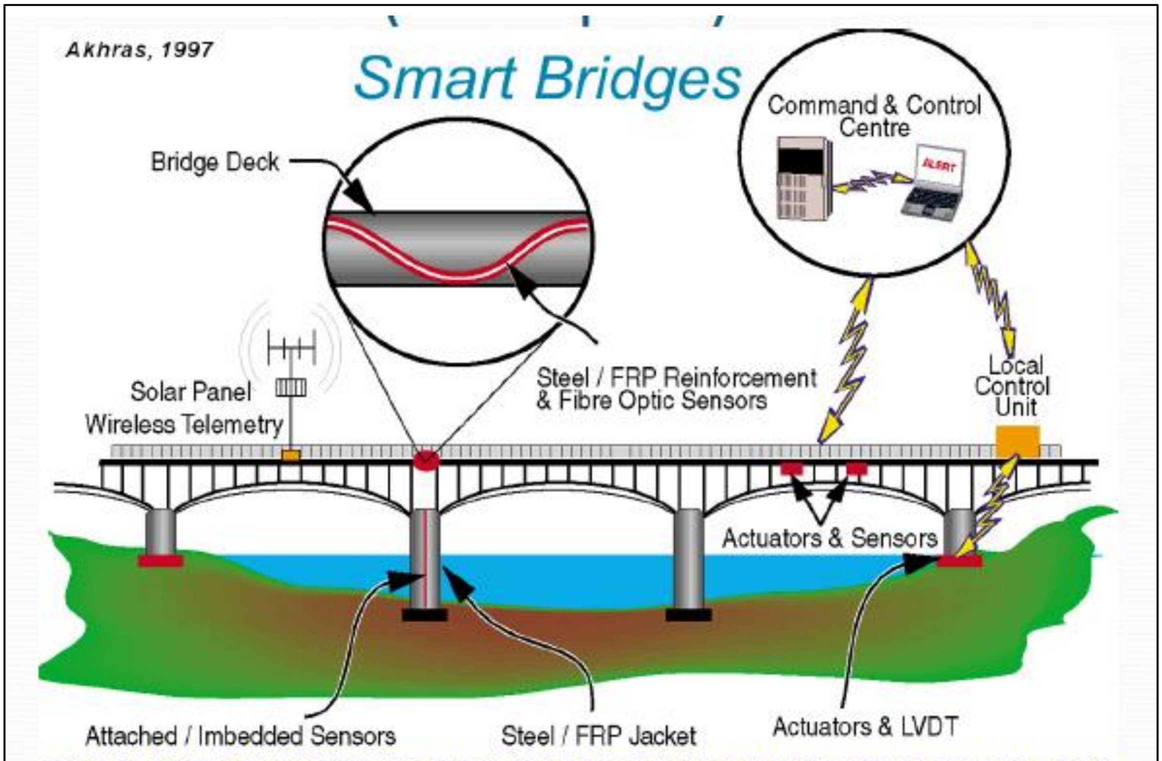
Smart Structure:

A smart structure is a system that incorporates particular functions of sensing and actuation to perform smart actions in an ingenious way.

The basic five components of a smart structure are

1. **Data Acquisition**: the aim of this component is to collect the required raw data needed for an appropriate sensing and monitoring of the structure.
2. **Data Transmission (sensory nerves):** the purpose of this part is to forward the raw data to the local and/or central command and control units.
3. **Command and Control Unit (brain):** the role of this unit is to manage and control the whole system by analyzing the data, reaching the appropriate conclusion, and determining the actions required.
4. **Data Instructions (motor nerves):** the function of this part is to transmit the decisions and the associated instructions back to the members of the structure.
5. **Action Devices (muscles):** the purpose of this part is to take action by triggering the controlling devices/ units.





Akhras, G. 1998, "How Smart a Bridge can be?" Proc., Canada-Taiwan Workshop on Medium and Long-Span Bridges, Taipei
Akhras, G. 2000, "Smart Materials and Smart Systems for the Future", Canadian Military Journal, Vol.1, No. 3, pp. 25-31

General Overview

Smart materials are materials that have one or more properties that can be significantly altered in a controlled fashion by external stimuli, such as stress, temperature, moisture, pH, electric or magnetic fields.

Examples:

A. Piezoelectric materials
B. Shape memory alloys
C. Magnetic shape memory alloys
D. Shape memory Polymers
E. PH sensitive polymers

A. **Piezoelectric materials** are materials that produce a voltage when stress is applied. Since this effect also applies in the reverse manner, a voltage across the sample will produce stress within the sample. Suitably designed structures made from these materials can therefore be made that bend, expand or contract when a voltage is applied.
B. **Shape memory alloys** and shape memory polymers are thermoresponsive materials where deformation can be induced and recovered through temperature changes, an example is Nitinol (Nickel Titanium).
C. **Magnetic Shape Memory alloys** are materials that change their shape in response to a significant change in the magnetic field.
D. **Shape-memory polymers (SMPs)** are polymeric smart materials that have the ability to return from a deformed state to their original shape induced by an external stimulus (trigger), such as temperature change.
E. **PH-sensitive polymers** are materials which swell/collapse when the pH of the surrounding media changes.

General Overview (Smart Structure Applications):

A. **Aerospace**
1. Damage detection
2. Vibration control
3. Shape control
4. Adaptive structures

B. **Defense**
1. Firing accuracy of weapons
2. Vibration and noise reduction in submarines
3. Smart missiles use smart fins which can warp to appropriate shapes

C. **Automotive**
1. Passenger comfort (noise control in cabin)
2. Vibration control (active engine mounts)
3. Health monitoring (smart sensors)

D. **Industrial**
1. Manufacturing (machine tool chatter control)
2. Air conditioning and ventilation (noise control)
3. Mining machinery (vibration control)

E. **Medical**
1. Smart sensors
2. Micro robotics
3. Surgical tools

F. **Civil**
1. Bridges
2. Earthquake protection

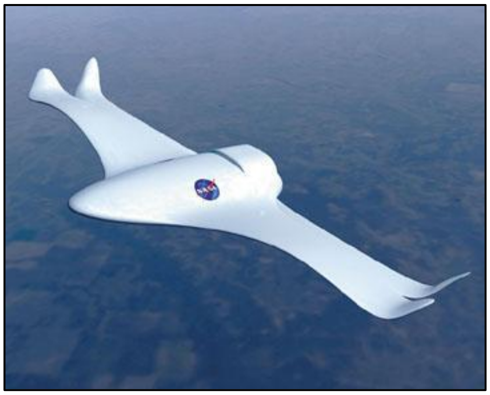
Smart materials (3 of 5): shape shifting material, drug delivering nano particles https://youtu.be/i6n8cpLKzHE

Applications of smart material:

- Smart switches & actuators (NiTi-long life)
- Safety device, fuse, alarms (CuZnAl-reliability)
- Artificial limbs, blood vessels & muscles (SM Polyurethane -bio compatibility)
- Adhesive tapes/bands (time bound adhesive property /painless removal/healing property)
- Food packaging industry-wrappers (adoptability)
- Smart spoons (Temperature sensitive polymers)
- Smart nose & tongue (recognition characteristics)
- Smart clothes (Adaptive to temperature changes)
- An "animated lamp" designed by Romolo Stanco that uses shape-memory alloy to change its shape whenever it's turned on and off.

- NiTi NOL wire – diameter in mm

- Aircraft which will incorporate "smart materials" that will allow the wings of a craft to change shape for optimal flying conditions.



- “Stealth Bombers” have ferro fluids on their outer “skin” to make them harder to spot with radar.

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SMART MATERIALS

Shape Memory Alloys

What are Shape Memory Alloys?

- An alloy that remembers” its original, cold-forged shape. By heating it returns back to the re-deformed shape.
- SMAs are materials which can revert back to original shape & size on cooling by undergoing phase transformations.
- Shape memory alloys (SMA's) are metals, which exhibit pseudo-elasticity and the shape memory effect.
- Examples: NiTiNOL (thermal), NiMnGa, Fe-Pd, Terfenol-D (Magnetic) CuZnSi, CuZnAl, CuZnGa, CuZnSn(actuator)
- The shape change involves a solid-state phase change involving a molecular rearrangement between Martensite and Austenite.
- A temperature change of only about 10^{o} C is necessary to initiate this phase change

Shape Memory Alloys

A. **Cu-based Alloys**
   1. Cu-Al-Ni with 14/14.5 wt.% Al and 3/4.5 wt.% Ni
   2. Cu-Sn approx. 15 at. % Sn
   3. Cu-Zn 38.5/41.5 wt.% Zn
   4. Cu-Zn-X (X = Si, Al, Sn)

B. **Other shape memory alloys include:**
   1. Ni-Ti (~55% Ni)
   2. Ag-Cd 44/49 at. % Cd
   3. Au-Cd 46.5/50 at. % Cd
   4. Fe-Pt approx. 25 at. % Pt
   5. Mn-Cu 5/35 at. % Cu
   6. Fe-Mn-Si
   7. Pt alloys
   8. Co-Ni-Al
   9. Co-Ni-Ga
   10. Ni-Fe-Ga

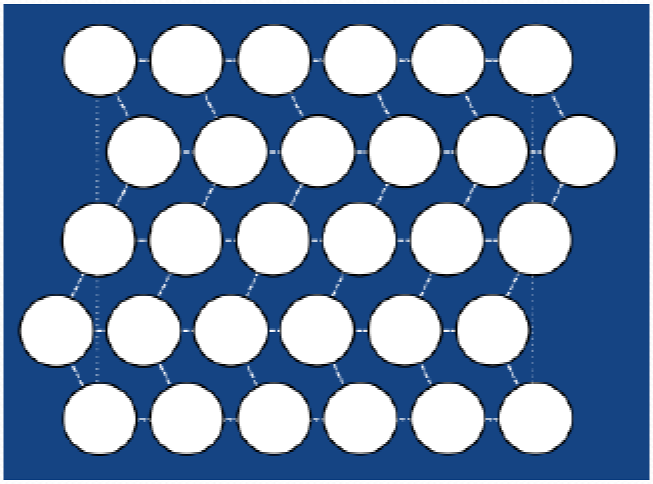
“Red” denotes major shape memory alloys.

The Shape alloys are currently being used in:

- The space shuttles
- Thermostats
- Vascular Stents
- Hydraulic Fittings (for Airplanes)
- Coffee pots

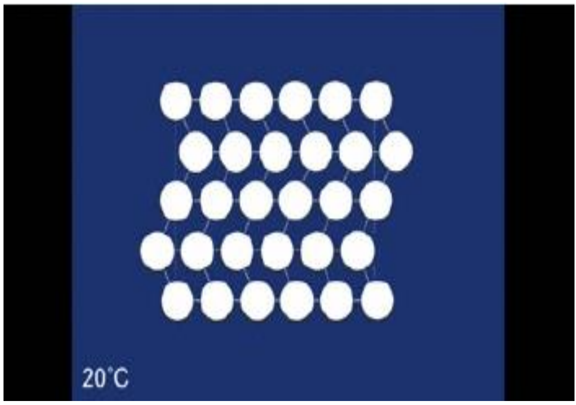
Shape memory effect

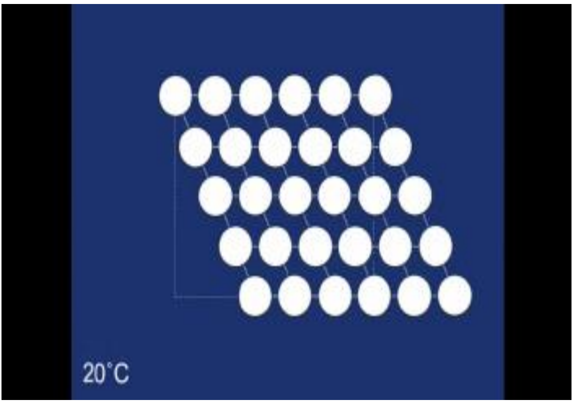
- The Shape memory effect is controlled by a structural rearrangement on the atomic scale. At room temperature the atoms from the structure shown below:

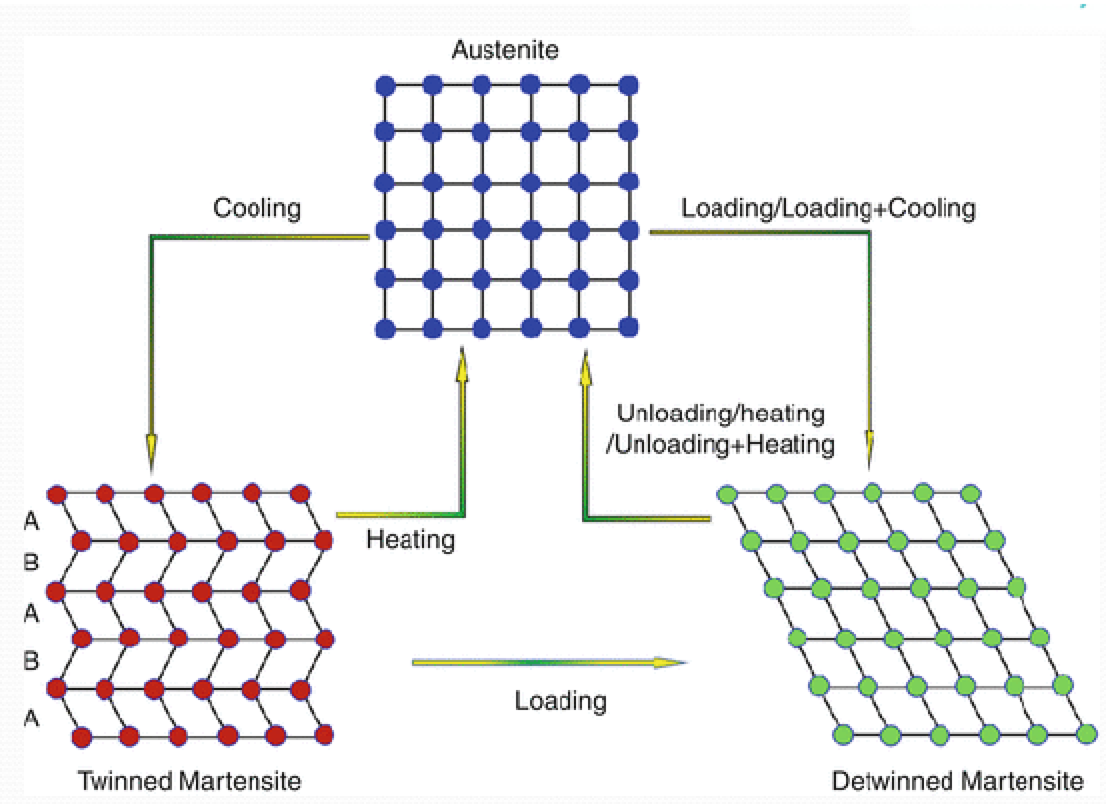


- The special property that allows shape memory alloys to revert to their original shape after heating is that their crystal transformation is fully reversible.
- This phenomenon results from a crystalline phase change known as "thermo-elastic martensitic transformation".
- At temperatures below the transformation temperature. shape memory alloys are
    - martensitic, In this condition. Their micro-structure is characterized by "self-accommodating twins “. The martensite* is soft and can be deformed quite easily by DE-twinning. Heating above the transformation temperature recovers the original shape and converts the material to its high strength austenitic condition.

* Martensite, named after the German metallurgist Adolf Martens (1850–1914)

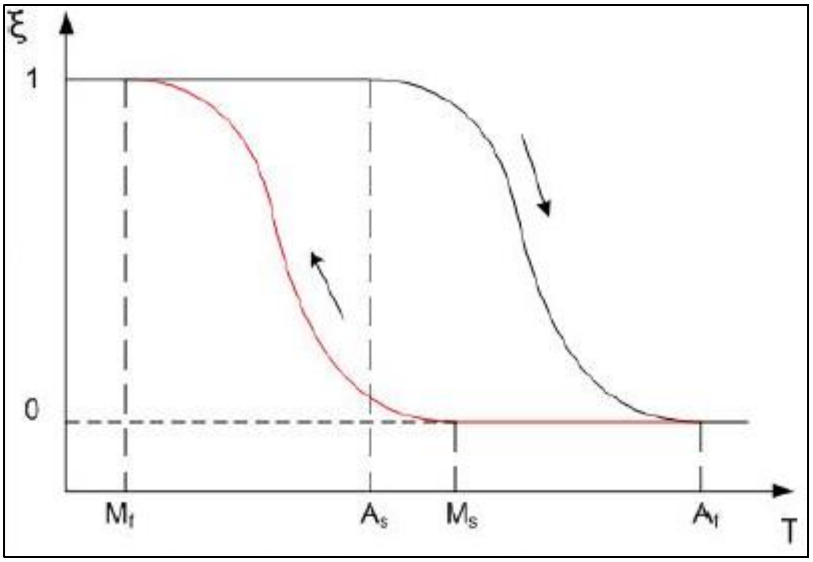






Super-elasticity and the Shape Memory Effect

A thermal reaction with no diffusion.



- In this figure, ξ(T) represents the martensite fraction. The difference between the heating transition and the cooling transition gives rise to hysteresis where some of the mechanical energy is lost in the process. The shape of the curve depends on the material properties of the shape-memory alloy.

- The transformation is reversible over temperature ranges determined during the formation of the material. NiTi alloys change from austenite to martensite upon cooling; M_f is the temperature at which the transition to martensite completes upon cooling. Accordingly, during heating A_s and A_f are the temperatures at which the transformation from martensite to austenite starts and finishes.

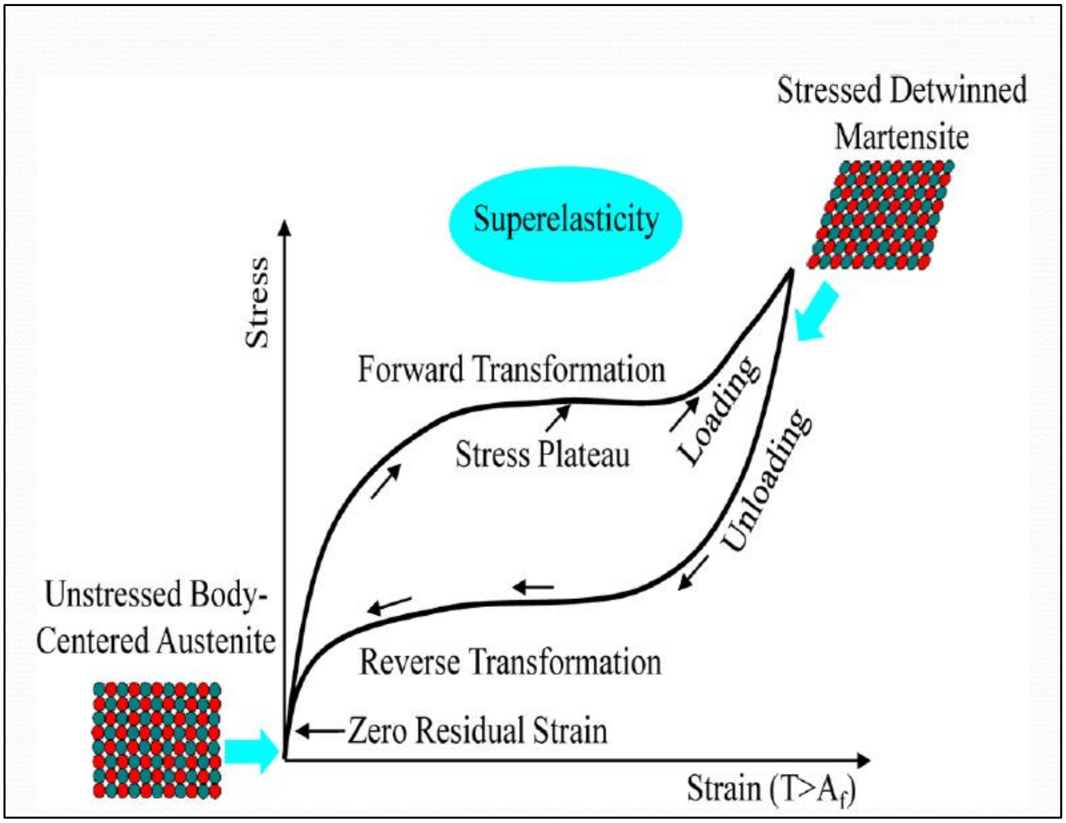
Martensite - Austenite Transformation:

Let's define the fraction of the martensite phase in the SMA as follows:

$$\xi = 0.5\left(\cos\left(\frac{\pi(T - M_f)}{M_s - M_f}\right) + 1\right) \text{ for the range of } M_f \leq T \leq M_s$$

similarly, we may write an expression for the transformation

$$\xi = 0.5\left(\cos\left(\frac{\pi(T - A_S)}{A_f - A_S}\right) + 1\right) \text{for the range of } A_S \leq T \leq A_f$$



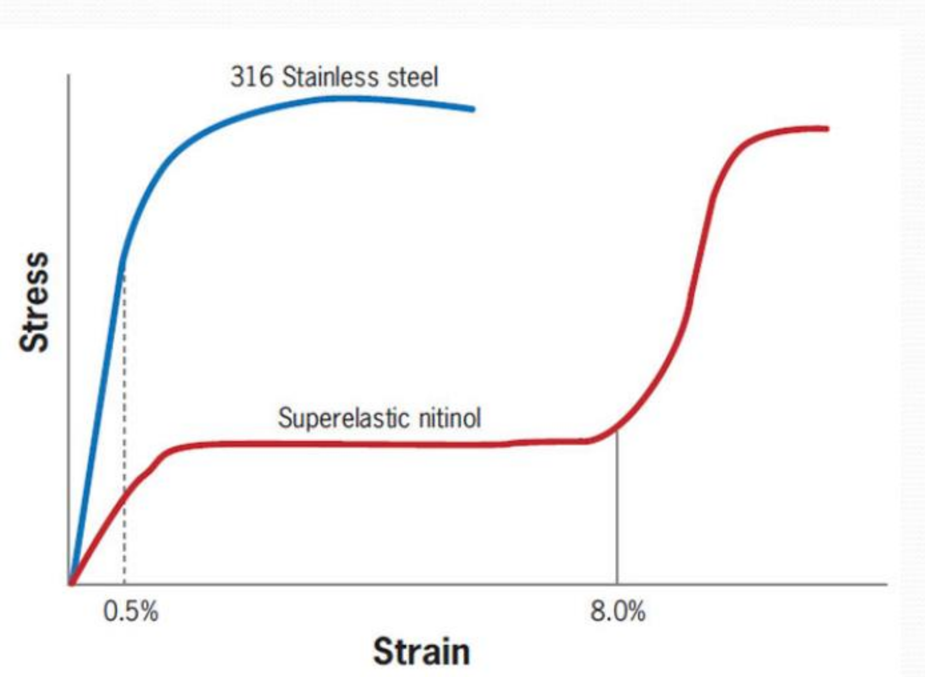
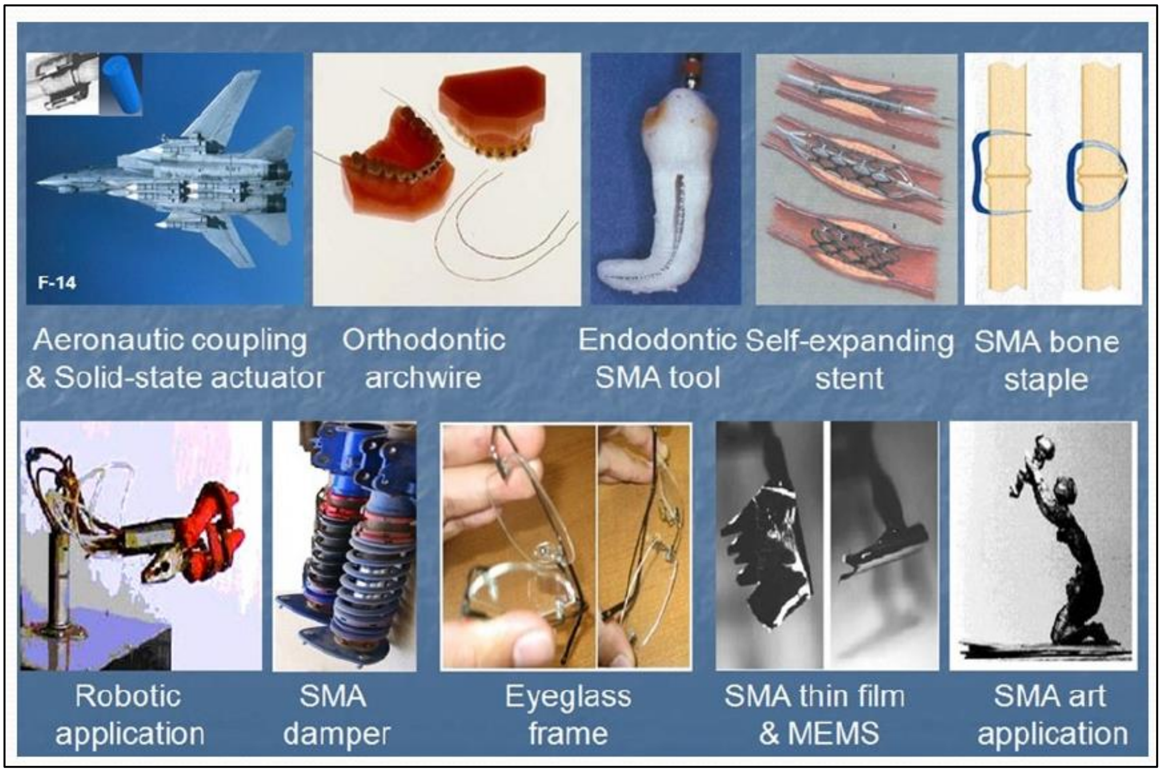


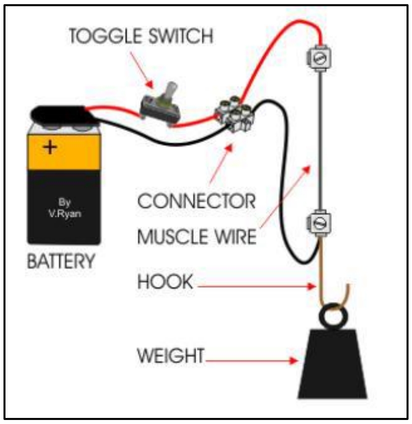
Figure 1. The elastic strain range for superelastic Nitinol compared to 316 stainless steel.



Applications for shape memory alloy

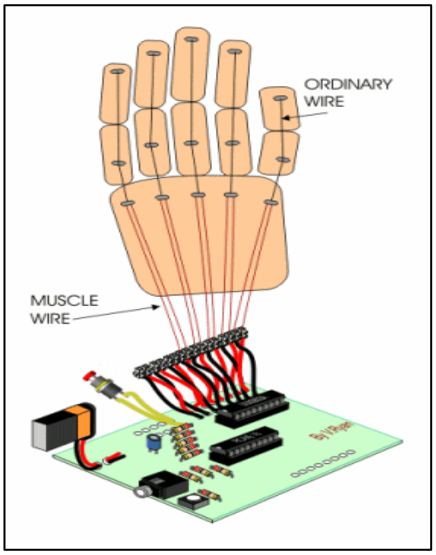
SMA in ROBOTICS – Muscle wire

- Muscle wire is NiTi alloy which can be stretched up to 8% of its length and still recover. (at room temp 3to5% stretch is possible)
- When a small current is passed through the wire it becomes much harder and returns to its original length with a reasonable force.
- A battery and switch are connected to muscle wire & a small weight stretches the muscle wire.
- The cycle of turning on and off the current has the effect of lifting and lowering of the weight.



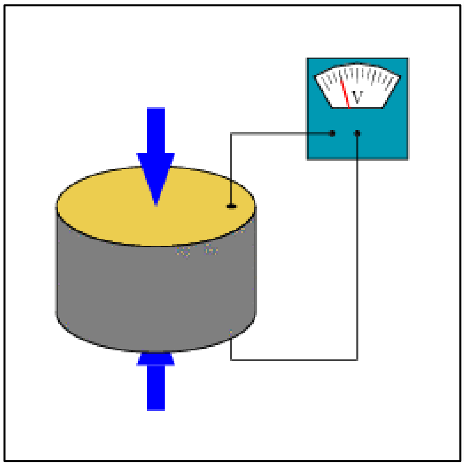
SMA in ROBOTICS – Robotic hand

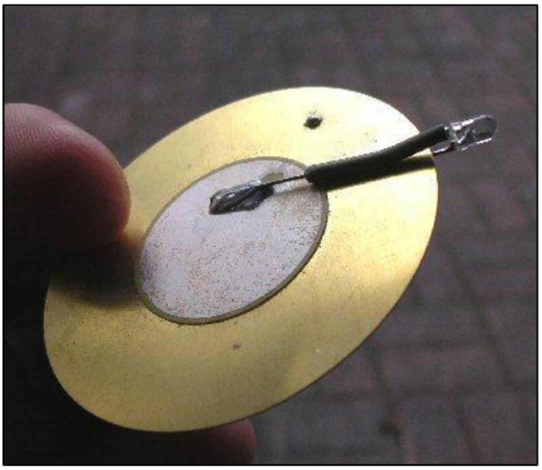
- A clever use of muscle wire and a micro-controller circuit is a robotic hand.
- A robotic hand has 'stretched muscle wires' attached to the base of each finger.
- When current is applied to the muscle wire it contracts to its 'natural' length by pulling on the ordinary wire.
- The micro-controller is programmed to give five of the outputs with switch on and off options.
- This makes the fingers of the hand move.



Piezoelectric Materials

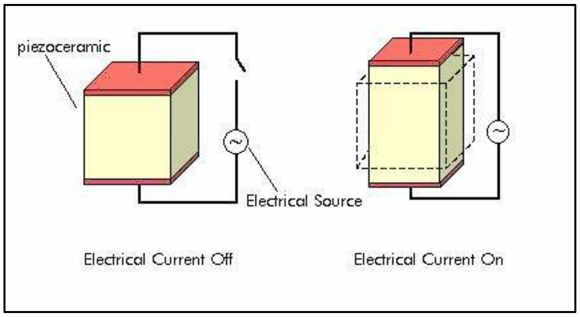
- Materials that produce a voltage when stress is applied. (An applied mechanical stress will generate a voltage)
- Example: Quartz, BaTiO3, GaPO4
- The piezoelectric effect describes the relation between a mechanical stress and an electrical voltage in solids.
- In physics, the piezoelectric effect can be described as the link between electrostatics and mechanics.
- An LED is wired to a piezoelectric transducer. The LED briefly lights when the device is flicked & shows that electricity has been generated by stress and strain.





Reverse Piezoelectric effect

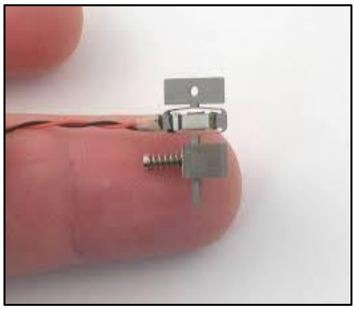
- An applied voltage will change the shape of the solid by a small amount (up to a 4% change in volume).
- Quartz watches, Piezoelectric US oscillator



Application of Piezoelectric effect

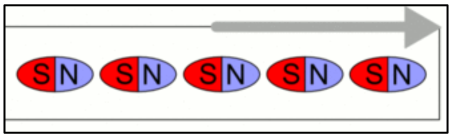
- In lighters or portable sparkers with a piezo fuze a sudden and strong pressure is used to produce a voltage. The spark then ignites the gas.
- A piezo motor is based on the change in mechanical shape of a piezoelectric material when an tension is applied. The material produces ultrasonic or acoustic vibrations and produces a linear or rotary motion.

- Piezo elements are used in music for acoustic instruments. They are inserted in stringed instruments such as guitar, violin or Mandolin. The dynamic deformation/vibration of the cords is converted into a small alternating voltage.



Magnetostrictive materials:

- Magneto striction is a property of ferro magnetic materials that causes them to change their shape or dimensions during the process of magnetization.
- The effect was first identified in 1842 by James Joule when observing a sample of iron.
- Ex: Fe, Co, Terfenol –D (US transducers, sonar, sound bug)



Magnetostrictive materials application:

Actuators and Sensors:

- Magnetostrictive transducers - Convert magnetic energy in to mechanical energy.

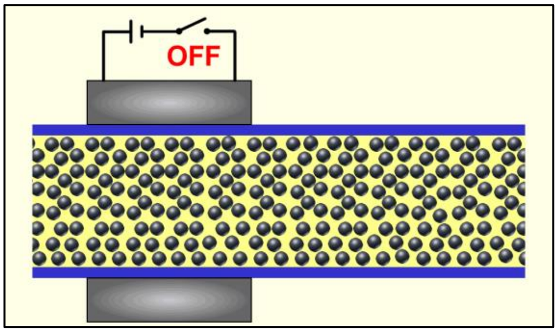
Vibration Speaker Technology

- using the highest power Smart Material. Install in seconds -peel and stick -no screws or mounting issues.
- High quality sound without design compromise. No wires, no boxes, no grilles.


Image courtesy of studioav.co.uk

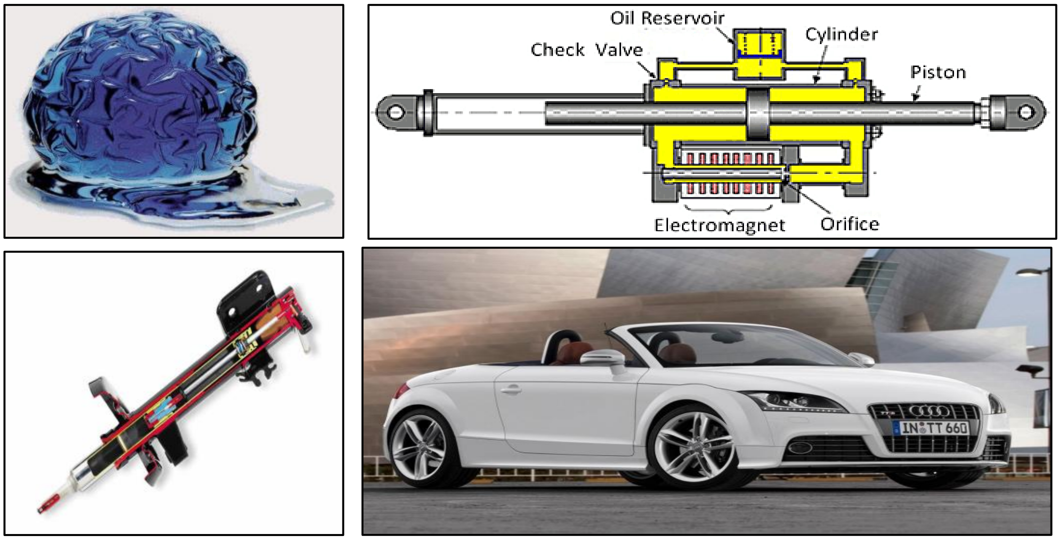
Magnetorheological fluids (MRFs):

- A MR fluid is a smart fluid which usually consists of 20-40 percent iron particles, suspended in mineral oil, synthetic oil, water or glycol.
- MRF also contains a substance which prevents the iron particles from setting.
- When subjected to a magnetic field, the magnetic particles inside increase the fluid's viscosity, rendering it viscoelastic solid.



MRF solidifying and blocking a pipe in response to an external magnetic field.

- “OFF" position – the MR fluid is not magnetized & the particles inside, distributed randomly, allow the fluid to move freely, acting like a damper fluid.
- “ON” position – the particles become energized and align into fibrous structures and restricts the movement of the fluid.



MRF – Applications