ANNAMACHARYA INSTITUTE OF TECHNOLOGY AND SCIENCES:: RAJAMPET
(An Autonomous Institution)

DEPARTMENT OF MECHANICAL ENGINEERING

LECTURE NOTES

SMART MATERIALS
[23A036ET]

ANNAMACHARYA INSTITUTE OF TECHNOLOGY AND SCIENCES RAJAMPET
(An Autonomous Institution)
Department of Mechanical Engineering

Title of the Course:	Smart Materials
Category:	Professional Elective – II
Couse Code:	23A036ET
Branch/es:	Mechanical Engineering
Year & Semester:	III Year II Semester

Lecture Hours	Tutorial Hours	Practice Hours	Credits
3	0	0	3

Course Objectives:

1. To understand the fundamental characteristics of different metals and gain insight into smart materials, including their classification and real-world applications.
2. To acquire knowledge of various types of smart materials, including electro-rheological fluids and shape memory materials.
3. To explore the processing techniques of smart materials and fluids, with emphasis on synthesis and fabrication methods such as metallization and UV curing.
4. To develop an understanding of different types of sensors, including advanced carbon nanotube and polymer-based sensors.
5. To comprehend the principles, types, and applications of actuators used in smart systems, including electro-thermal actuators.

Course Outcomes:

At the end of the course, the student will be able to

1. Explain and distinguish between traditional engineering materials and smart materials, and identify appropriate smart materials for various engineering applications.
2. Explain the working principles, properties, and applications of different smart materials and evaluate their suitability for specific engineering and technological applications.
3. Describe and apply suitable processing and fabrication techniques for different smart materials in engineering applications.
4. Identify, describe, and equate different sensor technologies and select appropriate sensors for engineering applications.
5. Demonstrate the working mechanisms of various actuators compare and select suitable actuation methods for different smart materials for create system applications.

Unit 1 **08**

Introduction: Characteristics of metals, polymers and ceramics. Introduction to smart materials. Classification of smart materials, Components of a smart System, Applications of smart material.

Unit 2 **08**

Smart Materials Piezoelectric materials, Electro strictive Materials, Magnetostrictive materials, Magnetoelectric materials, Magnetorheological Electrorheological fluids, Shape Memory materials.

Unit 3 **08**

Processing of Smart Materials Semiconductors and their processing, Metals and metallization techniques, Ceramics and their processing, Polymers and their synthesis, UV radiation curing of polymers, fluids.

Unit 4 **08**

Sensors Introduction, Conductometric sensors, Capacitive sensors, Piezoelectric sensors, Magnetostrictive sensors, Piezoresistive sensors, Optical sensors, Resonant sensors, semiconductorbased sensors, Acoustic sensors, polymerize sensors, Carbon nanotube sensors.

Unit 5 **08**

Actuators Introduction, Electrostatic transducers, Electromagnetic transducers, Electrodynamic transducers, Piezoelectric transducers, Electro-strictive transducers, Magneto-strictive transducers, Electro thermal actuators, Comparison of actuation, Applications

Prescribed Textbooks:

1. Smart Material Systems and MEMS: Design and Development Methodologies, V. K. Varadan, K. J. Vinoy, S. Gopalakrishnan, John Wiley and Sons, England, 2006
2. Smart Structures and Materials, Brain Culshaw, Artech House, London, 1996
3. Smart Materials and Structures, Mukesh V. Gandhi, Brian S. Thompson, , Springer, May- 1992.

Reference Books:

1. Smart Structures: Analysis and Design, A. V. Srinivasan, Cambridge University Press, Cambridge, New York, 2001.
2. Smart Structures, P. Gauenzi, Wiley, 2009.
3. Piezoelectric Sensorics: Force, Strain, Pressure, Acceleration and Acoustic Emission Sensors, Materials and Amplifiers, G. Gautschi, Springer, Berlin, New York, 2002
4. Analysis and Performance of Fiber Composites, B. D. Agarwal and L. J. Broutman, John Wiley & Sons
5. Engineering aspects of Shape memory Alloys, T. W. Duerig, K. N. Melton, D. Stockel,C.

Online Learning Resources:

- https://nptel.ac.in/courses/112104173/
- www.iop.org/EJ/article/0964-1726/5/3/002/sm6301.ps.gz
- https://nptel.ac.in/courses/112104173/
- https://nptel.ac.in/courses/112104251/

CO-PO Mapping:

Course Outcomes	Engineering Knowledge	Problem Analysis	Design/Development of solutions	Conduct investigations of complex problems	Modern tool usage	The engineer and society	Environment and sustainability	Ethics	Individual and team work	Communication	Project management and finance	Life-long learning	PSO1	PSO2
23A036ET.1	3	2	2	-	-	1	-	-	-	-	-	2	2	2
23A036ET.2	3	3	2	2	-	-	-	-	-	-	-	2	2	3
23A036ET.3	3	2	3	2	2	-	-	-	-	-	-	2	3	3
23A036ET.4	3	2	2	2	3	-	-	-	-	-	-	2	2	2
23A036ET.5	3	2	3	2	2	-	-	-	-	-	-	2	2	3

UNIT-I

1. "Stimuli-Response Behaviour" in smart materials

Defination

Stimuli-response behaviour means the ability of a material to sense change in its environment (stimulus) and respond to it in predictable and useful way.

Input (stimulus) → material reacts → out (response)

what is stimulus?

A stimulus is any external change such as

- Temperature
- stress or strain
- Electric field
- Magnetic field
- Light
- chemical environment
- moisture

what is the Response?

The material may respond by changing:

- shape
- size
- stiffness
- Color
- Electrical resistance
- viscosity

or any chemical or physical properties.

Examples of Stimuli-Responsive materials

1. shape memory alloys (SMA)
   - Stimulus: Temperature
   - Response: Returns to original shape when heated.
2. piezoelectric materials
   - Stimulus: Mechanical stress
   - Response: Generates electric voltage
3. Electroactive polymers
   - stimulus: Electric field
   - Response: changes shape
4. Magnetorheological fluids
   - Stimulus: Magnetic field
   - Response: Change viscosity
5. Thermochromic materials
   - Stimulus: Temperature
   - Response: Change color

why it is important (mechanical Engineering view)

- Sensors and actuators
- Adaptive structures
- vibration control system
- self healing materials
- Aerospace and biomedical applications

polymers

Polymers are long-chain organic molecules formed by covalent bonding.

Characteristics:

1. Low Density — light weight materials
2. Low strength — Not suitable for heavy loads
3. poor thermal conductivity — Good heat insulators
4. poor Electrical conductivity — used as insulators
5. Low melting point — Soften at moderate temperature
6. Good Corrosion Resistance — Do not rust easily
7. Good flexible and Elastic — Can undergo large deformation.

Examples:

- polyethylene (PE)
- PVC
- Nylon
- Rubber
- Teflon

Application

- packaging materials
- Plastic pipes
- Electrical insulation
- Medical devices

2. Metals

Characteristics:

1. Good electrical Conductivity
2. Good thermal conductivity
3. High strength
4. Ductile (Can be drawn into wires)
5. Malleable (Can be hammered into sheets)
6. Shiny (lustrous surface)
7. High density
8. Generally high melting point

Mechanical Behaviour

- Tough and Strong
- undergo plastic deformation before fracture

Examples:

- steel, Aluminium, copper, Iron, Titanium

Application

- Machine Component
- Automobile parts
- Structures
- Electrical wires

Defination of metals

Metals are materials having metallic bonding and crystalline structur.

Ceramics

Ceramics are inorganic, non-metallic materials with ionic or Covalent bonding.

Characteristics

1. Very Hard and Wear Resistant
2. High Compressive Strength
3. Brittle Nature - Break suddenly without plastic deformation.
4. Very high Melting point
5. poor Electrical Conductivity (mostly insulators)
6. Excellet wear Resistance
7. Good Chemical and Corrosion Resistance

Examples

- Alumina (Al_2O_3)
- Silicon Carbide (SiC)
- Glass
- Cement
- Porcelian

Applications

- Cutting tools
- Refractory linings
- Electrical insulators
- Engine components

3. What are Smart materials

Defination

Smart materials are materials that can sense changes in their environment (stimuli) and respond automatically in a useful and controlled manner.

(or)

Smart materials are materials that respond to external stimuli such as temperature, stress, electric field, magnetic field, light, or pH by changing their properties like shape, stiffness or electrical characteristics.

Classification of smart materials

1. piezoelectric materials
2. Electro strictive materials
3. Magneto strictive materials
4. Magnetoelectric materials
5. Magnetorheological materials (or) fluids
6. Electrorheological materials (or) fluids
7. shape memory alloys
8. Chromic materials
9. Electroactive materials
10. Self healing materials
11. Adaptive Composite materials
12. smart structural system.

(a) piezoelectric materials

Stimulus: Mechanical Stress

Response: Generate electric charge

→ They convert mechanical energy into electrical energy and vice versa.

Examples: Quartz, PZT

Application: Sensors, Actuators, ultrasonic devices.

(b) Electrostrictive materials

Stimulus: Electric field

Response: Mechanical deformation

→ They change shape when electric voltage is applied.

Application: precision Actuators, micro position devices.

(c) Magnetostrictive Materials

Stimulus: magnetic field

Response: change in length or dimension.

→ when a magnetic field applied the materials expands or contracts.

Examples: Terfenol-D

Application: Actuators, vibration control,

(d) Magnetoelectric Materials

Stimulus: Magnetic field

Response: produce electric polarization

→ This materials shows Coupling between magnetic and Electric properties.

Applications: Sensors, transducers, memory devics

(e) Magnetorheological fluids (MR)

Stimulus: Magnetic field

Response: Change in viscosity

→ Fluid changes from liquid to semi-solid state under magnetic field.

Application: Shock absorbers, Clutches dampers.

(f) Electrorheological fluids (ER)

Stimulus: Electric field

Response: Change in viscosity

velocity increases when electric field is applied

Application: Adaptive Suspension systems.

(g) Shape memory Alloys (or) Materials

Stimulus: Temperature

Response: Recover original shape

→ They return to their original shape when heated after deformation.

Example: Nitinol (Ni-Ti alloy)

Application: Biomedical stents, aerospace Components.

4. Components of a smart System

A smart system is an integrated system that can sense, process, decide and act automatically in response to environment changes.

1. Sensor (Input Element)

- Detects physical changes like temperature pressure, strain, light, vibration etc
- Convert physical quantity into electrical signal.

Examples:

- piezoelectric sensor (stress → voltage)
- Thermocouple (temperature → voltage)
- strain gauge (strain → resistance change)

2. Transducer

- converts one form of energy into another.
- sometimes sensor and transducer are combines.

Example:

- Microphone (sound → Electrical signal)

3. Signal Conditioning unit

- Amplifies weak signals
- Filters noise
- converts analog signal into digital signal

→ Important because raw sensor signal is usually weak and noisy.

4. Controller/processor

- Brain of the system.
- Receives processed signal.
- Compare with reference value.
- Makes decisions using programed logic

Examples:

- Microcontroller
- Microprocessor
- programmable Logic Controller (PLC)

5 Actuator (output element)

- produces mechanical movement or physical Change.
- Converts electrical signal into ~~elec~~ Mechanical action.

Examples

- Shape memory Alloy
- piezoelectric actuator
- Electric motor

6. feed back system

- Measures output
- sends output data back to controller
- maintains accuracy and stability

→ Forms a closed loop system.

7 power supply

- provides energy to sensors, controller and actuators.
- Can be better or external power source.

5. Advantages of smart materials

1. Self Actuation Capability

→ Can act as both sensors and Actuators.
→ Reduces need for complex mechanical system.

Examples: piezoelectric materials.

2. High precision and fast response

→ provide accurate control
→ Respond quickly to external stimulus.

3. Compact and lightweight

→ Reduce size and weight of systems.
→ Important in aerospace and robotics.

4. Energy Efficiency

→ Converts energy directly (mechanical electrical)
→ less energy loss compared to conventional system.

5. Reduced maintaince

→ fewer moving parts
→ Less wear and tear.

6. Adaptability and Automation

→ Automatically adjust to environmental changes.
→ Improves systems performance and safety.

7. Multi functionality

→ one material can perform multiple functions (sensing + actuation)

Limitations of smart materials

1. High cost

→ Expensive manufacturing process

→ Advanced materials like SMA and PZT are costly.

2. Limited force output

→ Some materials produce small force

→ Not suitable for heavy load application

3. Complex Control System

→ Require advanced electronics & controllers

→ Increases system complexity

4. Temperature sensitivity

→ performance may vary with temperature

→ SMA properties depend strongly on temp.

5 material fatigue

→ Repeated actuations can reduce life.

→ SMA may lose memory effect over cycles

Application of smart materials

1. Aerospace Engineering

2. Biomedical Applications

3. Robotics

4. Automotive Industry

5. Defense Application

6. Electronics.

UNIT-II

Smart materials

1) Piezoelectric materials

Principle

"Piezoelectric materials" are a Class of materials that generate an electric Charge when subjected to mechanical stress and conversely, undergo mechanical deformation when an electric field is applied. This reversible electromechanical behaviour enables both sensing and actuation.

There are two fundamental piezoelectric materials

1. Direct piezoelectric effect
   - Mechanical stress → Electrical Charge
   - used in Sensors and energy harvesting.
2. Converse piezoelectric effect
   - Electrical field → mechanical deformation
   - used in actuators and precision motion devices.

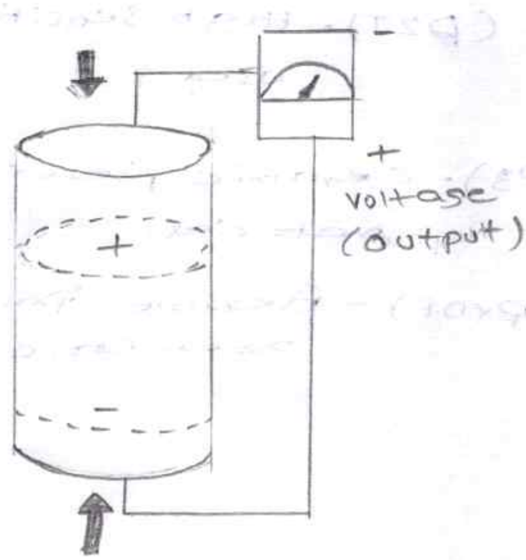


fig: Direct piezoelectric effect

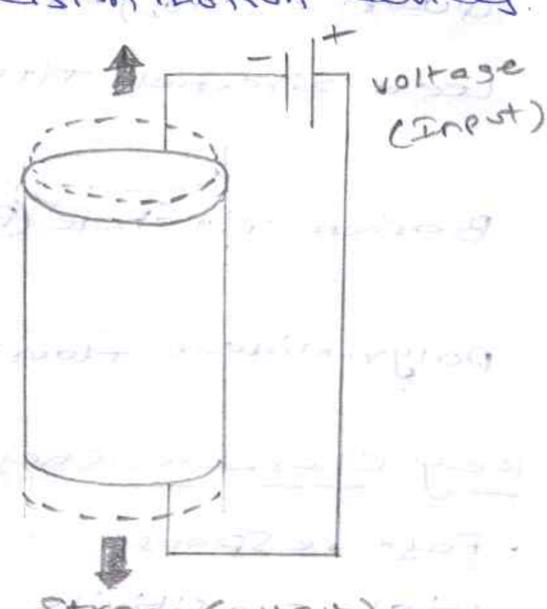
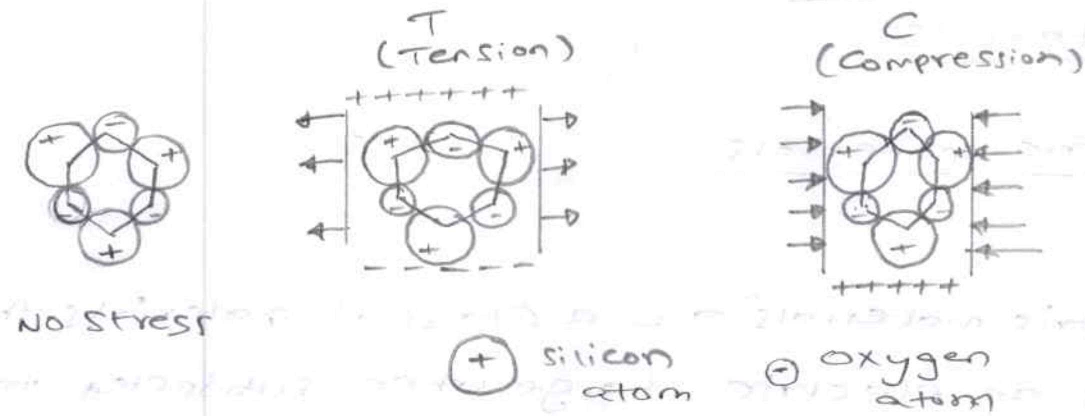


fig: converse piezoelectric effecteer



Working principle:

→ when a mechanical force (Compression / tension is applied,
→ The internal crystal structure get deformed
→ positive and negative charge centers shift.
→ This creates an electric dipole moment
→ Hence, electric voltage is produced across the material.

Common piezoelectric materials

Quartz (SiO_2) - stable, used in oscillators

Lead zirconate titanate (PZT) - High sensitivity widely used.

Barium Titanate ($BaTiO_3$) - Ceramic piezoelectric material.

polyvinlidene flouride (PVDF) - flexible polymer piezoelectric

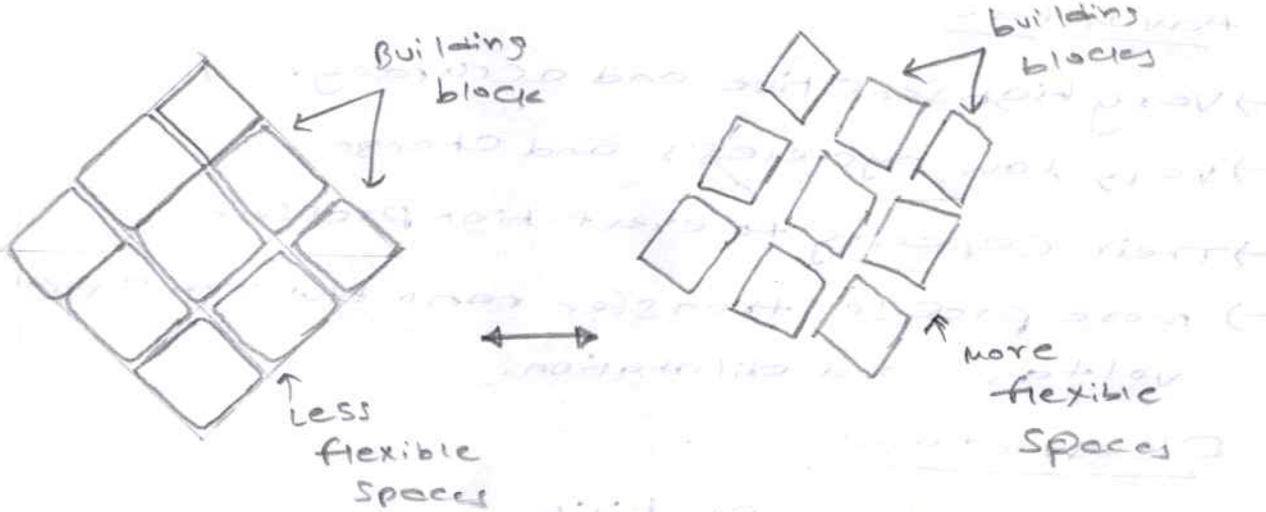
Key Characteristics

- Fast response
- High sensitivity
- Small displacement
- works in dynamic condition

2) Electrostrictive Materials

"Electrostrictive materials" are materials that undergo mechanical deformation (strain) when subjected to an electric field.

→ Unlike piezoelectric materials, electrostriction occurs in all dielectric materials, but the effect is significant only in certain ceramics and polymers.



Electrostriction is quadratic electromechanical coupling phenomenon in which the induced strain is proportional to the square of the applied electric field, regardless of the field direction.

$$\text{Strain} \propto E^2$$

Working principle

Upon subjection to an electric field the positively charged ions seperate, thereby changing the dimension of the cell and resulting an expansion

→ Dimensional change of a material under the influence of applied electric field.

→ The main differance b/w electrostrictive and piezoelectric materials is that the first doesn't show spontaneous polarization. The lack of spontaneous polarization means that electrostrictive materials display little or no hysteresis even at higher frequencies.

Advantages

→ Very high sensitive and accuracy.

→ very low hysteresis and charge.

→ Their capacity to exert high pressure.

→ more precise transfer ratio b/w the applied voltage and dilatation.

Disadvantages

→ very low temp stability.

→ The electrical capacitance is 4-5 times as high as piezoelectric materials.

→ Impossible to generate negative strain.

Application

1) optical alignment devices

2) precise positioning systems

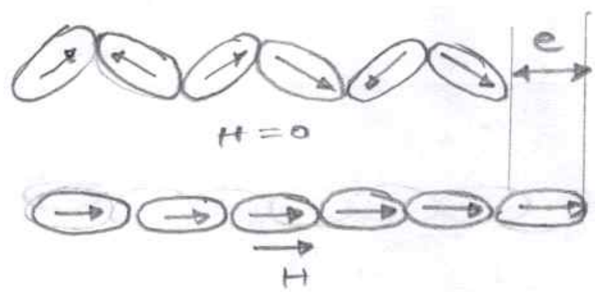
3) fine motion control systems

4) Adaptive optics

3) <u>Magneto Strictive materials</u>

→ Magical power of magnets awed people of early civilization as a strange force from the rocks that attracts shoes and swords without revealing itself.

→ In <u>1842</u>, James Joule noted that ferromagnetic sample changed its length with the application of magnetism.



→ Magnetostriction (e) in material due to domain migration and reorientation under applied magnetic field H.

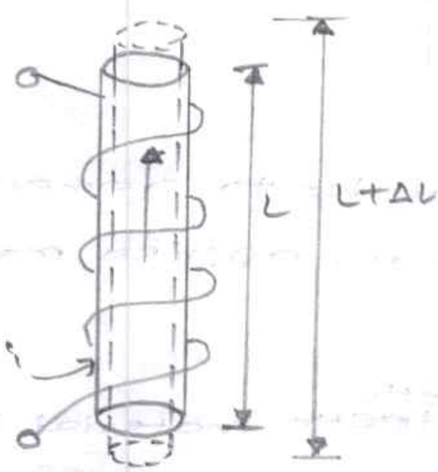
→ If a crystal of ferromagnetic material is intially at a compressed state, the effect of magnetostriction becomes more pronounced.

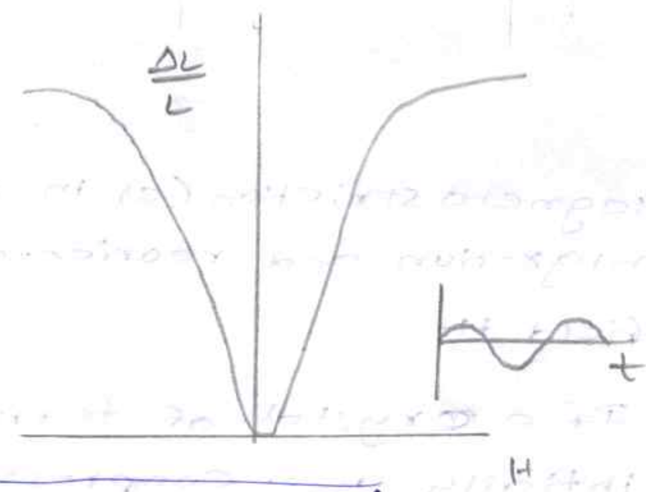
→ All ferromagnetic materials shows magnetostriction to different degree.

→ It is observed that the maximum one can achieve is for Cobalt which saturates around 50 μ strain (ppm).

Some magnetostrictive materials

Material	Magnetostriction (ppm)	Curie temp (K)
Fe	14	633
Ni	33	1043
Co	50	350
permalloy	27	713
$DyFe_2$	650	636
$TbFe_2$	2630	703
$Tb6DY7Fe_{1.9}$	2400	653





Joule Effect: $S_1 = \sigma_1 / E_p + d_m H$

Villary Effect: $B = d_m \sigma_1 + \mu H$

where, σ - stress, S = Strain, B - magnetic displacement

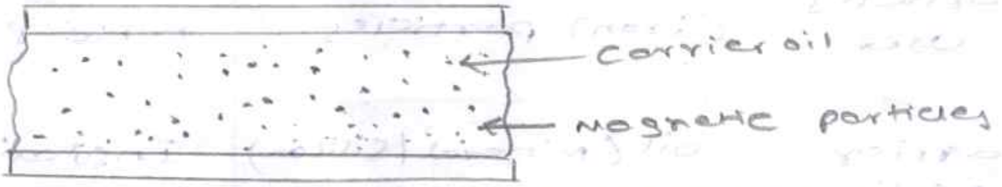
μ - permeability, d_m - magneto. constant

Application

1. Sonar system (Defense)
2. position Sensor
3. Actuators

4) Magnetorheological fluids

A "magnetorheological fluid" is a type of smart fluid which, when subjected to a magnetic field greatly increases in apparent viscosity, to the point of becoming a viscoelastic solid.



→ Magnetorheological fluid when not exposed to a magnetic field.

→ Magnetorheological fluid when a magnetic field is applied.

Electroheological fluids

Electroheological (ER) fluids are "smart" suspensions that transition from a liquid to a gel-like solid in milliseconds when an electric field is applied, reversing immediately when it is removed.

→ Exhibit the Bingham effect changing from a liquid to a semi-solid under an electric field.

→ The field forces suspended particles into chain-like structures, creating a field-dependent yield stress (τ_y) below which act as solids and above which they flow as Bingham plastic.

$$\tau = \tau(E) + \eta_{pl} \cdot \dot{\gamma}$$

Magnetorheological V/s Electrorheological fluids

Aspect	Magnetorheological (MR) fluid	Electrorheological fluid
1. Controlling field	Magnetic field	Electric field
2. particles used	Ferromagnetic (iron) particles	Dielectric (nonmagnetic particles)
3. Carrier medium	oil (mineral / silicon)	Insulating oil
4. Voltage required	Low voltage (12-24v)	High voltage (1-5kv)
5. Current requirement	High Current	Low Current
6. Yield stress	High	Low
7. Load capacity	Suitable for heavy loads	Suitable for Light loads.
8. Sensitivity	Less sensitivity	Sensitive to moisture
9. Cost	Higher	Lower
10. Application.	Shock absorbers, dampers, vibration Control.	Clutches, valves precision devices.

5) ## Shape memory alloys (SMA)

"Shape memory alloys (SMA)" are the alloys which change its shape from its original shape to new shape and while heating/cooling it will return to its original shape.

→ SME was first observed in 1932 in Gold Cadmium Alloy.

→ Three types of SMA are currently popular

- CuZn Al
- Cu Al Ni
- NiTi (1962)

The last one is commercial available as NitiNOL. (NOL - Naval ordinance Laboratory, USA)

Shape memory Effect

These are two common types,

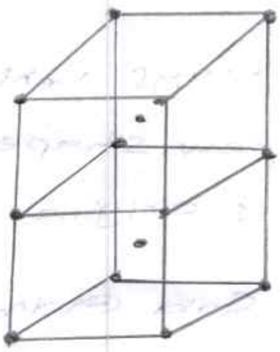
- One way effect: the material always remember the shape at the parent state (Austenite phase).
- Two way effect: the material is trained to remember two shapes one the parent Austenite phase and other at the martensite phase

Manufacturing SMA

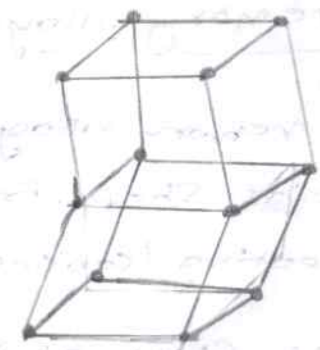
→ Shape memory alloy are typically made by casting using vacuum arc melting or induction melting.

→ These are specialized techniques used to keep impurities in the alloy to a minimum and ensure the metals are well mixed.

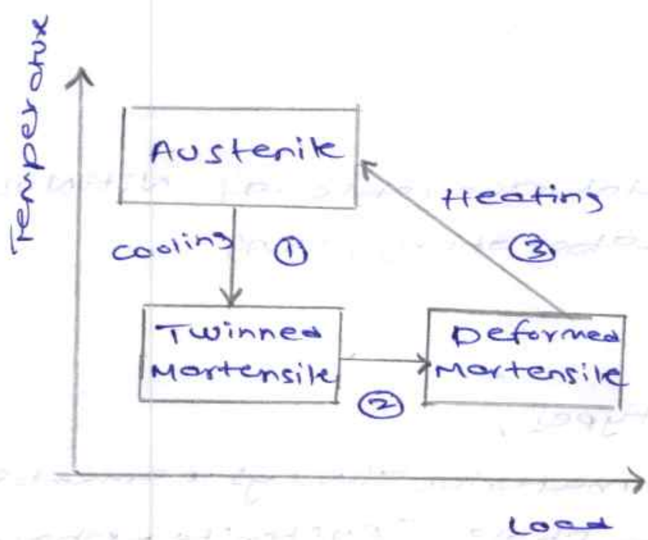
→ The ingot is then hot rolled into longer section and subsequently drawn to convert it into wire.

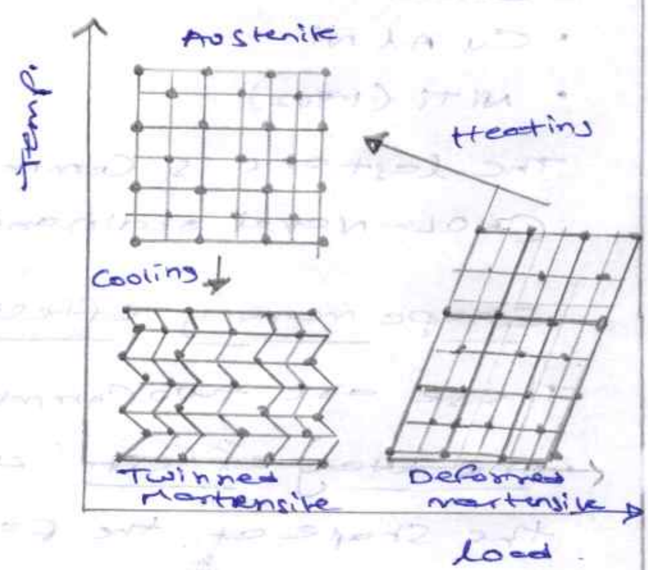


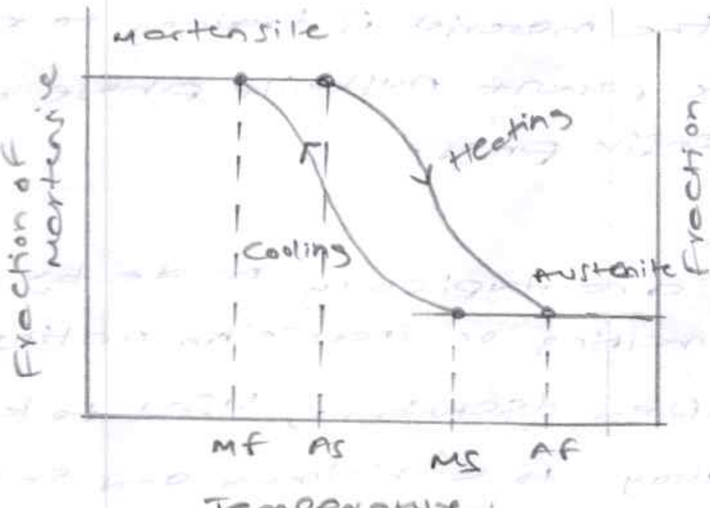
Austenit Structure



Martensite Structure







Application

Medicine, Engines, Aerospace, Robotics, Automotive, Civil Structures, Textile.