Smart Materials for Fuzing

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Outline

- Presentation Objective: Review several smart materials and potential applications to fuzing and ordnance
- Smart material overview
- Piezoelectrics
  - *Damage sensing, power harvesting*
- Shape Memory/Superelastic Alloys
  - *IM, self-healing, safe & arm applications*
- Magneto/Electro-rheological Fluid
  - *Suspension, safe & arm*
- Conclusions

Smart Material Classification

- Materials converting energy/fields into other (especially mechanical)
- Many definitions, other names and related areas
  - *Intelligent materials, multifunctional materials*

	Electric Field	Magnetic Field	Thermal Energy	Light	Chemical Energy
Actuation	**Piezoceramics Piezopolymers Electrostrictors Electrorheological fluids**	**Magnetostrictors Magnetorheological fluids**	**Shape memory alloys, ceramics, polymers**	**Light activated gel (Becker and Glad 2000) Laser driven flyer plates**	**Ionic polymers**
		Force Displacement		Force Displacement	
Sensing	**Piezoceramics Piezopolymers Electrostrictors Electrorheological fluids**	**Magnetostrictors Magnetorheological fluids**	**Shape memory alloys, ceramics, polymers**	**Fiber optics**	**Ionic polymers**
	Charge, capacitance resistance	Resistance, inductance	resistance	Light intensity, frequency	Concentration, pH

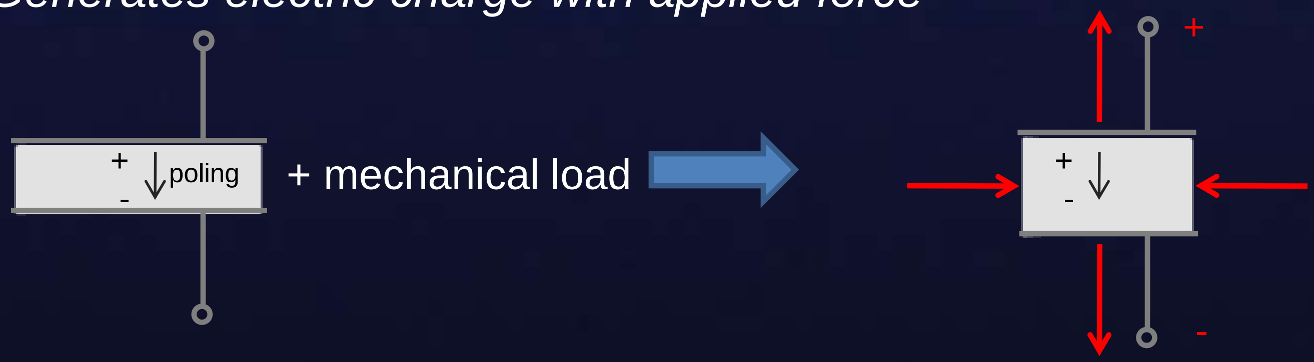
- Smart structures use these materials to provide integrated sensing, actuation or control and structural integrity

Why Consider Smart Materials?

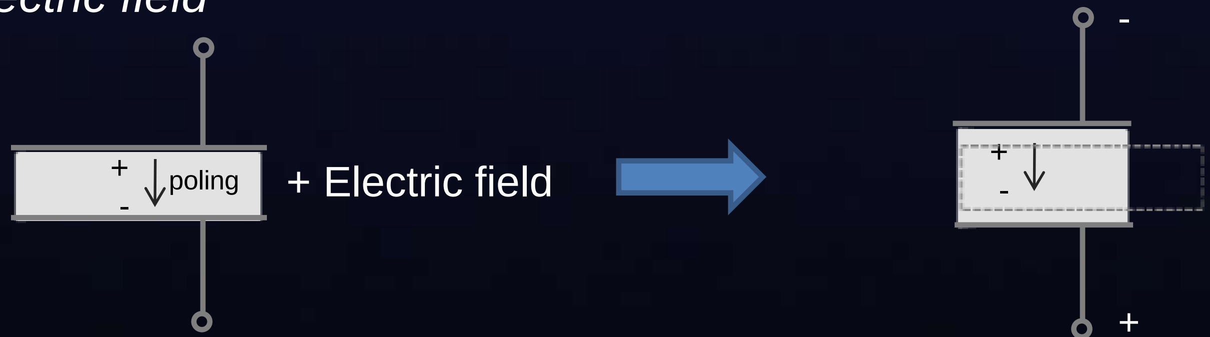
- Increased functionality
  - *Monitoring functions*
    - As munitions age, increased likelihood of malfunctions.
    - Sensing solutions can help predict individual or subpopulation reliability
  - *Environment sensing*
    - Both during storage and at use
  - *Adaptivity*
    - Shape morphing and control
    - Self repair
- Reduced size
  - *Higher energy density*
  - *Smaller munitions*
  - *Smarter munitions*
    - Fit more into the provided space
      - Integrated fuzing guidance and targeting

Piezoelectric Background

- Generally high force/ low stroke
- Direct effect
  - *Generates electric charge with applied force*



- Converse effect
  - *Generates mechanical force/ displacement from electric field*



Piezoelectric Material Background

- Piezoelectric effect found in crystals, ceramics polymers and biological materials
- Common piezoceramics lead zirconate titanate (PZT), Barium titanate, lead metaniobate (PMN)
- PZT – high piezoelectric and dielectric constants
    - Many formulations of PZT exist – Hard, soft
- DOD-STD-1376 - Originally defined standard material types for Hydrophones
    - *DOD or Navy Type I- VI*
    - *Hard or soft, Curie point, Self heating susceptibility (high electric drive potential)*
- Manufacturers generally report material properties

Material Modeling

- 3D constitutive equations

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 \\ s_{21}^E & s_{22}^E & s_{23}^E & 0 & 0 & 0 \\ s_{31}^E & s_{32}^E & s_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66}^E = 2\left(s_{11}^E - s_{12}^E\right) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \epsilon_{11} & 0 & 0 \\ 0 & \epsilon_{22} & 0 \\ 0 & 0 & \epsilon_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

- Simplified to one dimension

$$S_1 = s_{11}^E T_1 + d_{31} E_3$$

$$D_3 = d_{31} T_1 + \varepsilon_{33}^T E_3$$

Typical Material Constants

PZT 5H (Navy Type VI)					
d_{31} (m/V)	d_{33} (m/V)	Elastic modulus (N/m^2)	Density (kg/m^3)	ε^T_{33} (F/m)	Curie temp (°C)
-320×10^{-12}	650×10^{-12}	6×10^{10}	7800	3.36×10^{-8}	230

$$+\begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

$d_{33} \sim 2x\ d_{31}$

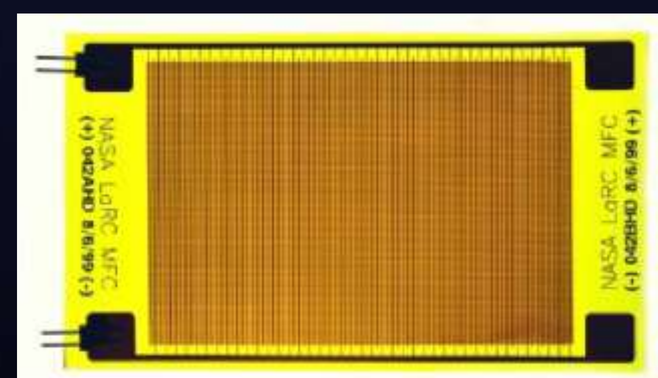
Since E is scaled by distance (V/m) field applied across thin dimension

Common Configurations

- Patch
  - *Generates /responds to plate and beam bending and tensile/compressive waves*
  - *Unimorph and bimorph configurations*
- Stack
  - *Takes advantage of d_{33} coefficient*
- MFC
  - *Uses d_{33} coefficient for in-plane motion*

Stack actuators from APC International
www.americanpiezo.com

Patch actuator



MFC actuator

Piezo Sensing/Actuation Examples

Sensing

- *Accelerometer*
- *Power harvesting*
- *Passive damping – shunting (skis)*

Actuation

- *Atomic force microscope position control*
- *Speakers*
- *Buzzers*
- *Anything "ultrasonic" (humidifiers, cleaners)*
- *Depth finders/SONAR*

Sensing/ actuation

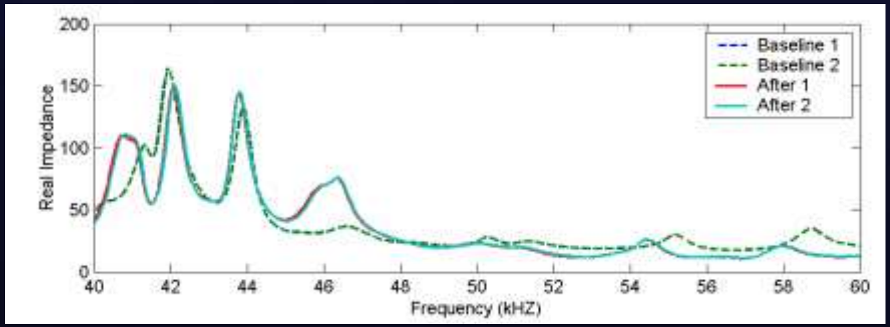
- *Structural monitoring*
- *Vibration control*

Current Fuzing Applications

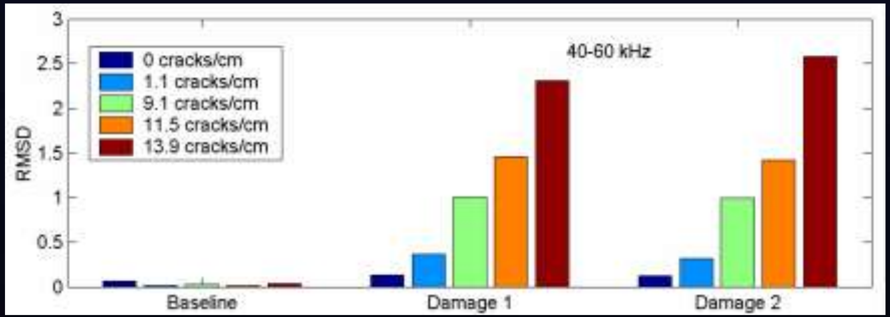
- Dozens of piezoelectric fuze patents
- Rocket Propelled Grenade
  - *Acceleration at launch strains* ***piezoelectric fuze*** *that ignites primer.*

Piezo-Based SHM

- Utilizes high frequency vibrations to detect local changes in materials
  - *Stiffness changes due to cracking*
  - *Increases in damping*
  - *Interface changes such as loosening of a joint.*
- Electrical impedance is directly related to mechanical impedance
- Wave propagation approach can also be utilized
  - *Measure reflections, attenuation, delay due to damage*



Impedance response

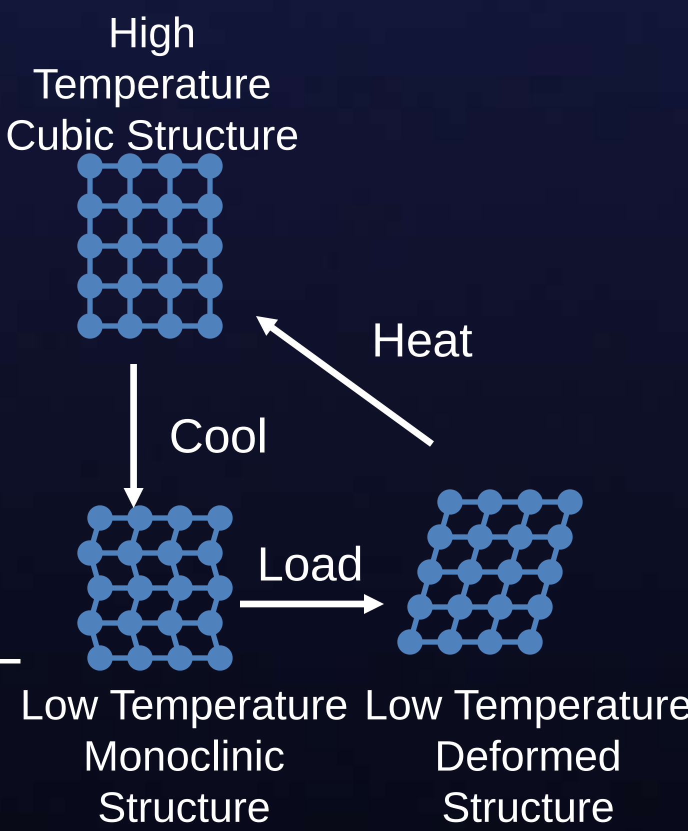


Damage Metric

Matrix cracking in carbon fiber composite

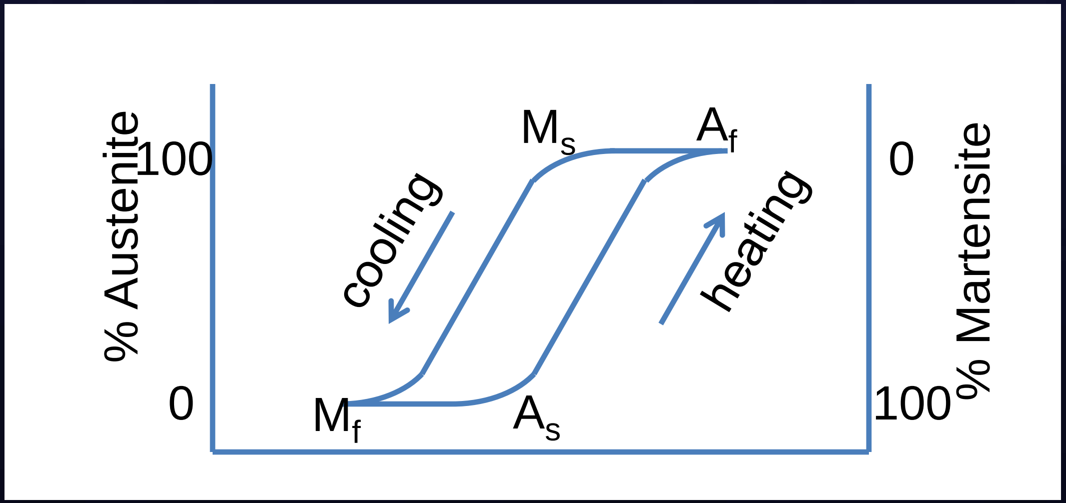
Shape Memory Alloy

- NiTiNOL developed at Naval Ordnance laboratory
- Shape memory effect : result of change in crystal structure
  - *Martensite at low temperature- **twinned** crystal structure*
  - *Austenite at high temperature- body centered cubic*
  - *Reverts to original undeformed shape when heated beyond transition temperature*
  - *One-way and two-way effects*
- Stress can also cause transition – Superelastic effect
- 6-8% strain
- Relatively slow response time
  - *Speed increased for low volume (faster temperature change)*



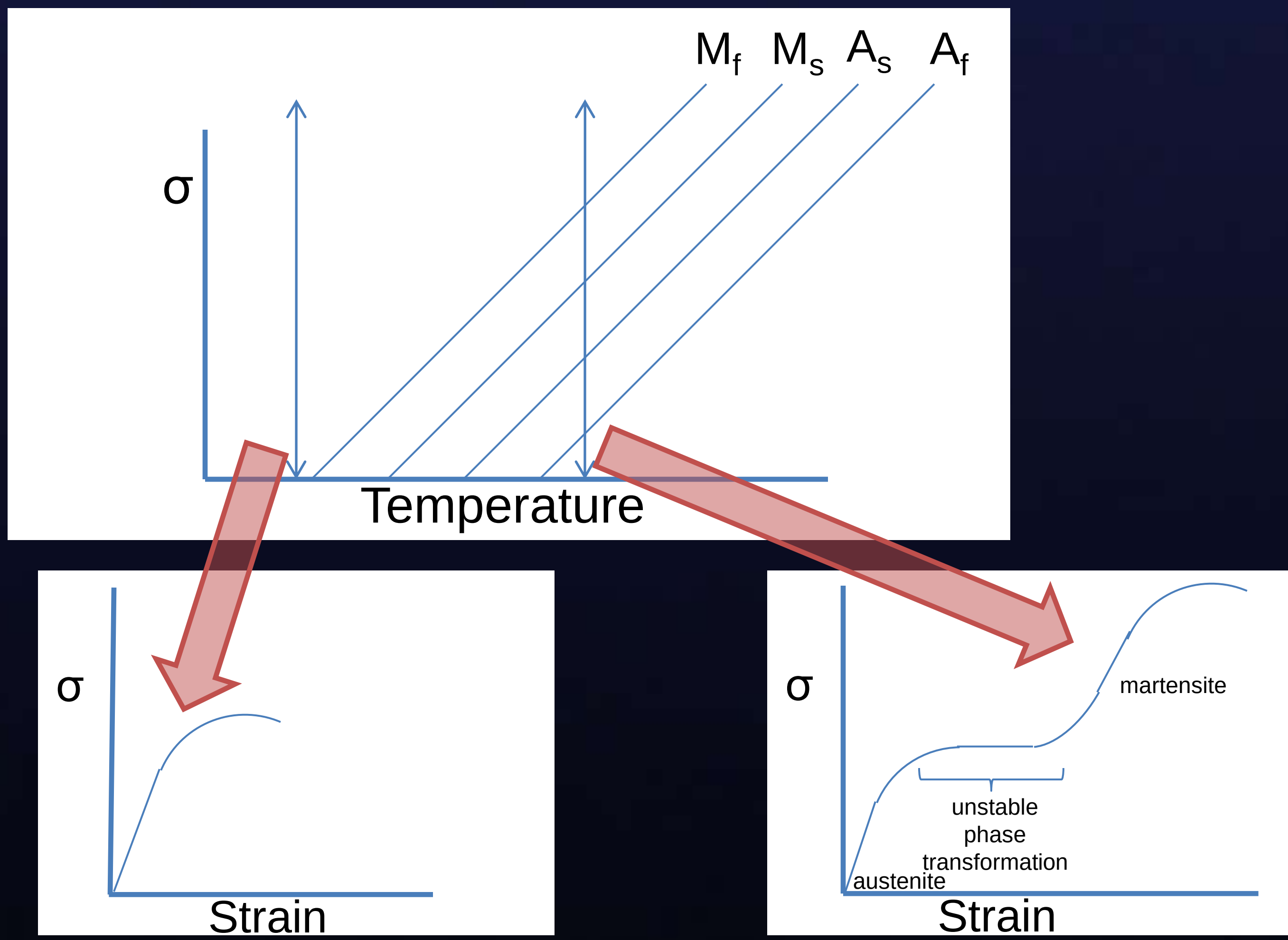
Temperature Transition

- Width and temperature of hysteresis can be controlled
- State dependent on path to current temperature



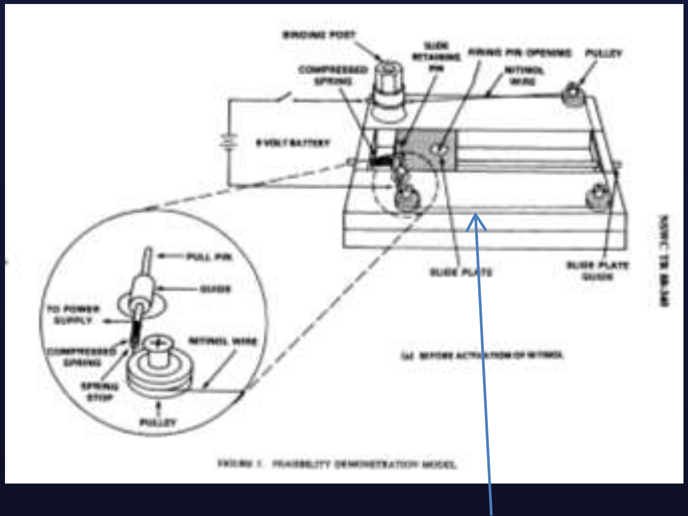
Superelastic Behavior

- Stress-strain curve depends on material temperature relative to transition temperature



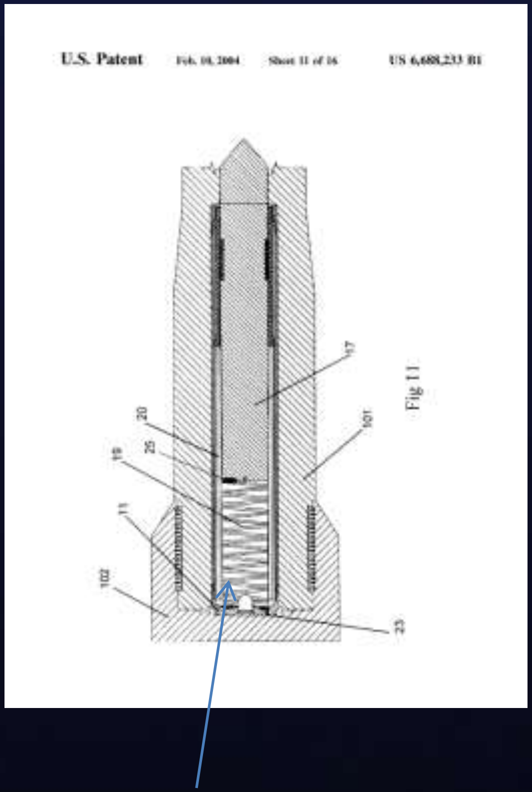
SMA Fuzing Examples

- Damping
- S&A actuation
  - *Goldstein and Weiner*
  - *Investigated effects of prestrain on transition temperature*
    - Activation temperature up to 150 C
- Non-pyrotechnic separation systems
- IM compliance
  - *Marchand et al. - Mine Clearance System rocket-towed linear demolition charge makeover*
  - *SMA proposed for release rocket motor case at both ends and actuate thermal igniter for Slow-Cook mitigation*
- Manufacturing
  - *Removable fixturing*



Reusable SMA Projectile Translation

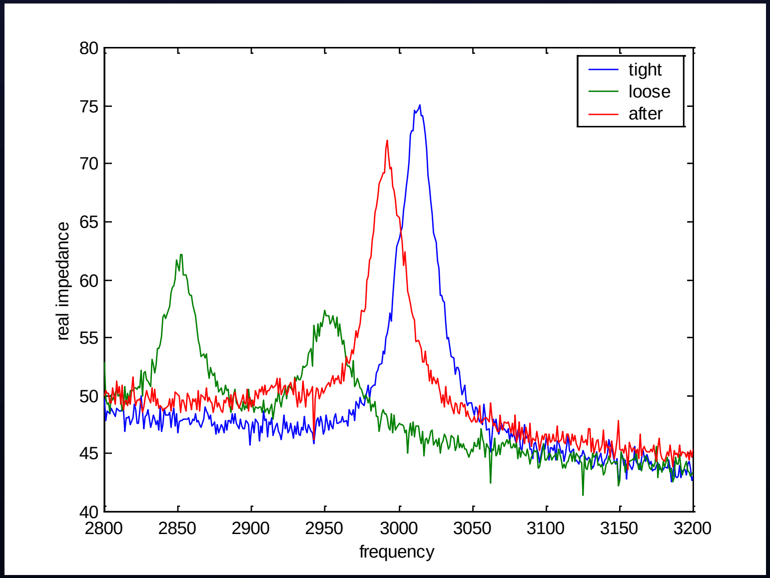
- Recoil, launch stress can be reduced by translating projectile a small distance forward prior to launch
- Typically accomplished by secondary charge
  - *Not reusable if launch is aborted*
- SMA spring suggested for Cased Telescoped Ammunition
- Manole et al. 2004 US patent 6,688233B1



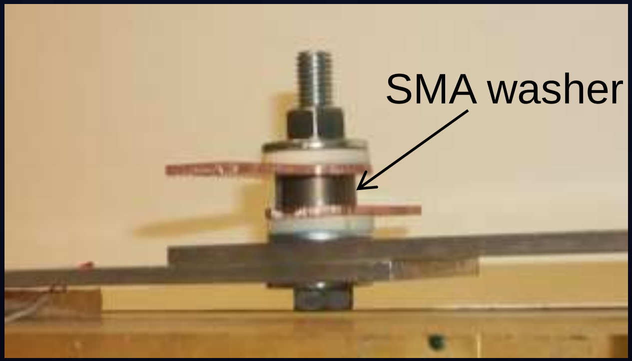
SMA spring

Self-Healing Bolted Joint

- Proof-of-concept testing
- Heated with external heater or resistively
  - *Competing for electrical and thermal isolation and high stiffness*
- Joint tightness monitored with PZT
- SMA ring sized to provide tension to compensate for reduced torque tightening

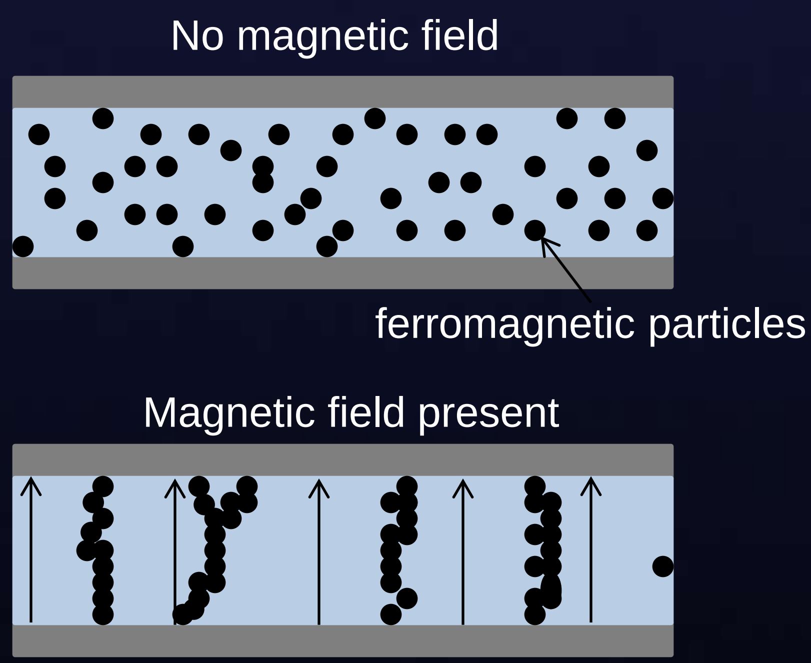


Impedance response of joint



Magnetorheological (MR) Fluids

- Change viscosity with magnetic field
- Response times on order of 10 ms
- Viscoelastic solid below yield stress when field applied
  - *Field dependent modulus*
- Newtonian fluid when field is off

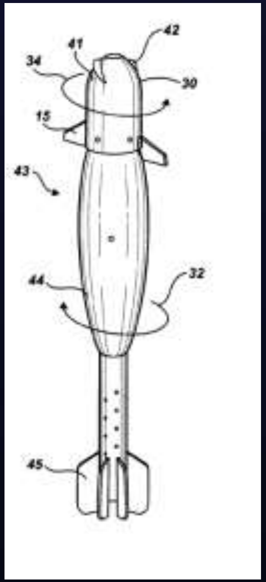


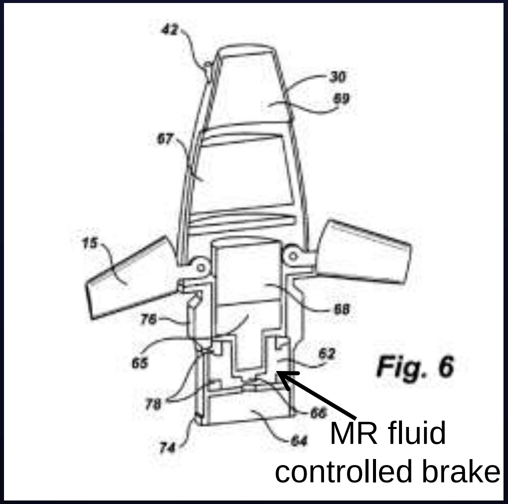
Possible Fuze Application

- Research on self-regulation of delay arming time of MR fluid fuze (Hu et al. 2010, Jiaxing University and Nanjing University of Science and Technology)
  - *Permanent magnet used to keep MR fluid as a solid during storage*
  - *Setback causes magnet to separate and rod impacts a piezo energy harvester*
  - *Energy harvester charges capacitor*
  - *Capacitor discharges into coil to regulate MR fluid viscosity*
  - *MR fluid viscosity controls flow through an orifice to control arm time*

MR Fluid Braking

- Morris et al., US Patent 7354017, 2008, Projectile trajectory control system
- Used to control de-spin of a projectile with braked rotating fins.





Summary and Conclusions

- Smart Materials offer alternative sensing and actuation systems
  - *Piezoelectric materials provide both sensing and actuation at high speed and forces, but low displacement*
  - *SMA provides high displacement and forces, but low speed*
  - *MR fluid provides fast response time and relatively high forces*

- Numerous unexplored applications for these materials exist including in the fuzing and ordnance environment