Shape Memory Alloys

Corso Materiali intelligenti e Biomimetici
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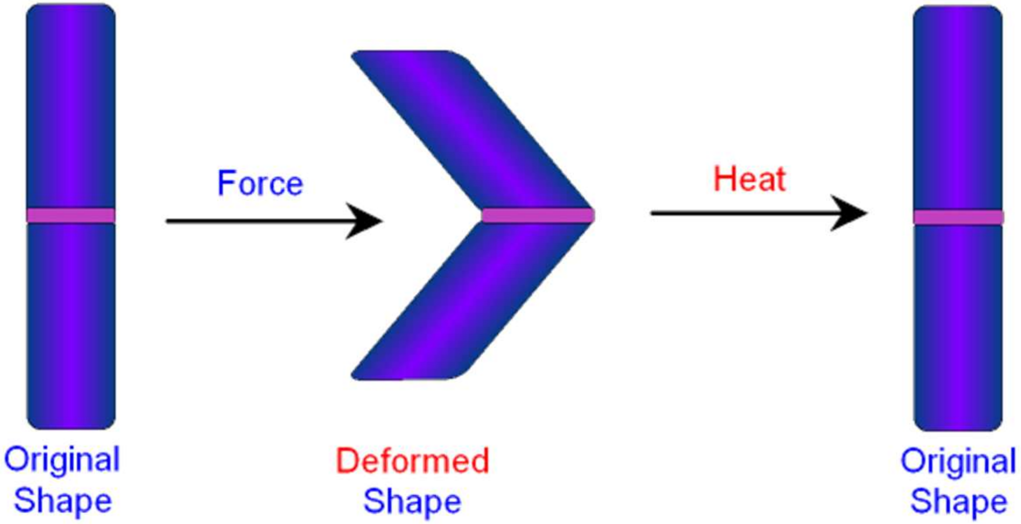
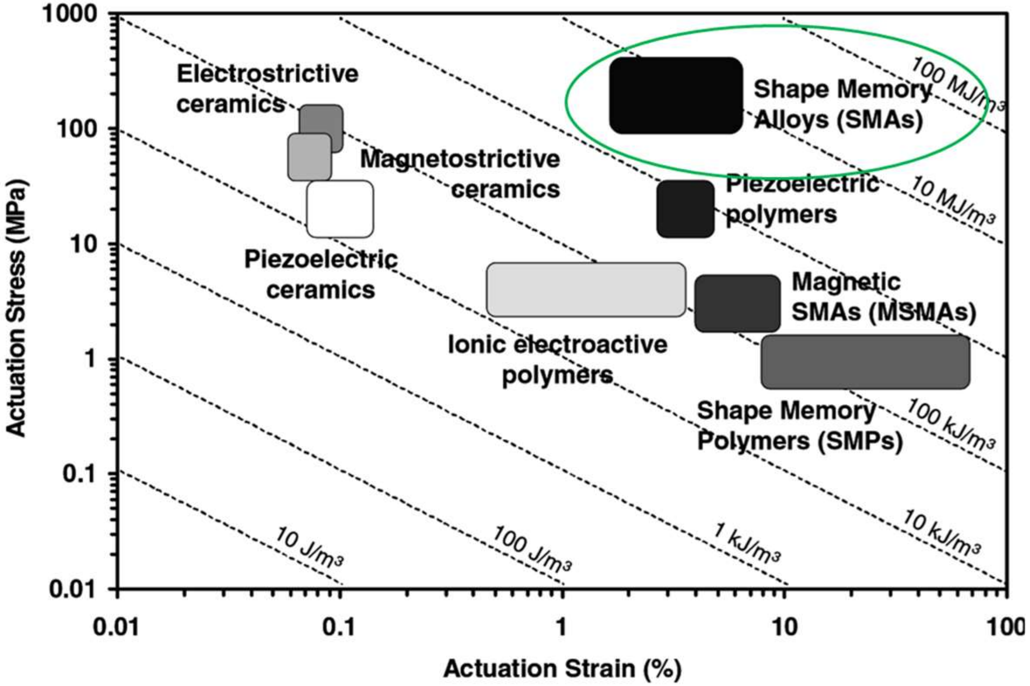
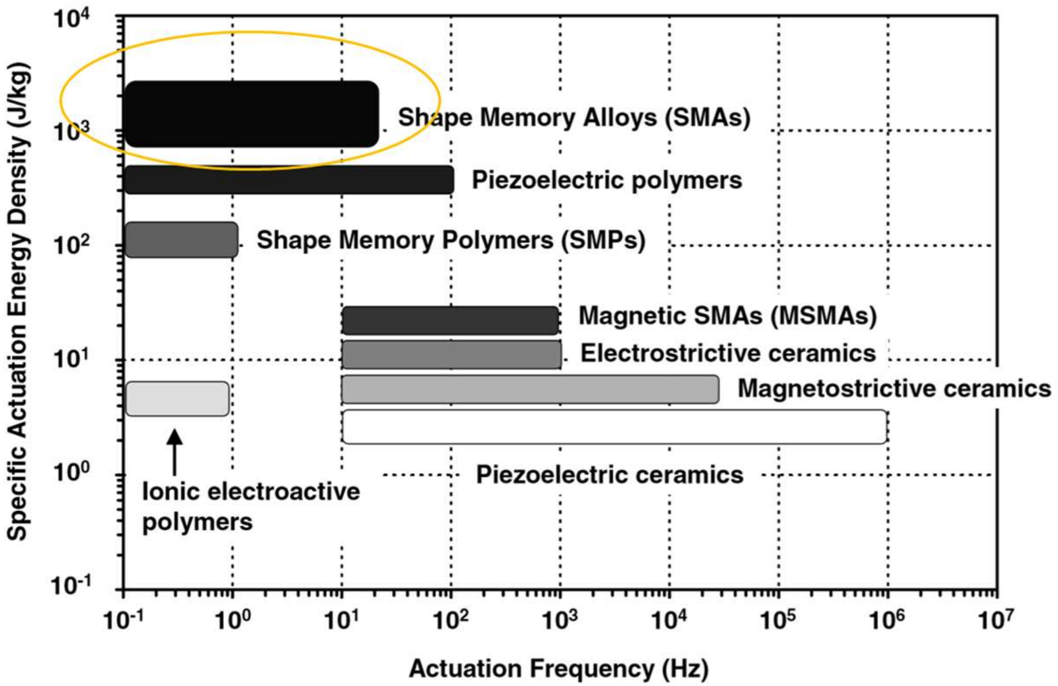
SMAs

Shape Memory Alloys (SMAs) are a unique class of shape memory materials with the ability to **recover their shape when the temperature is increased -> TERMOMECHANICAL *coupling***

An increase in temperature can result in shape recovery *even under high applied loads* therefore resulting in **high actuation energy densities**.





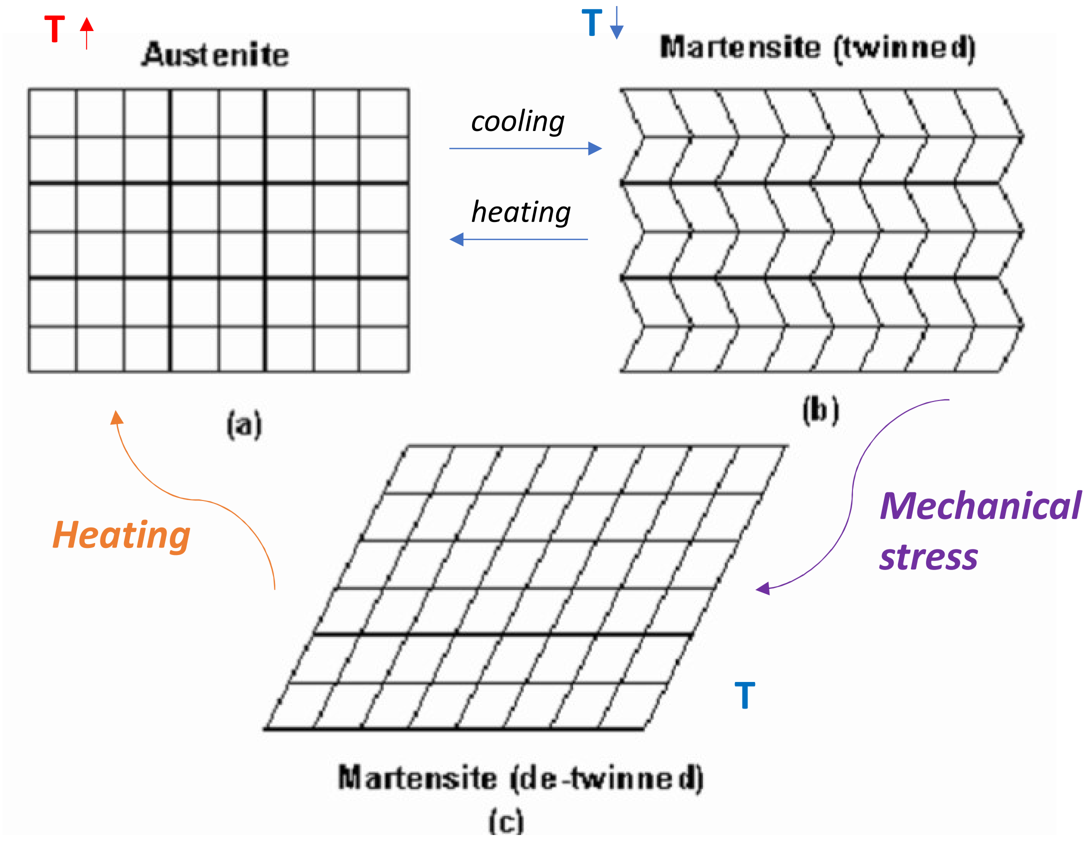


SMAs:

\+ high actuation energy densities

\- low frequency response

Crystalline structures



- In **austenite phase** (T>Ta), the crystalline structure of the material is cubic (a).

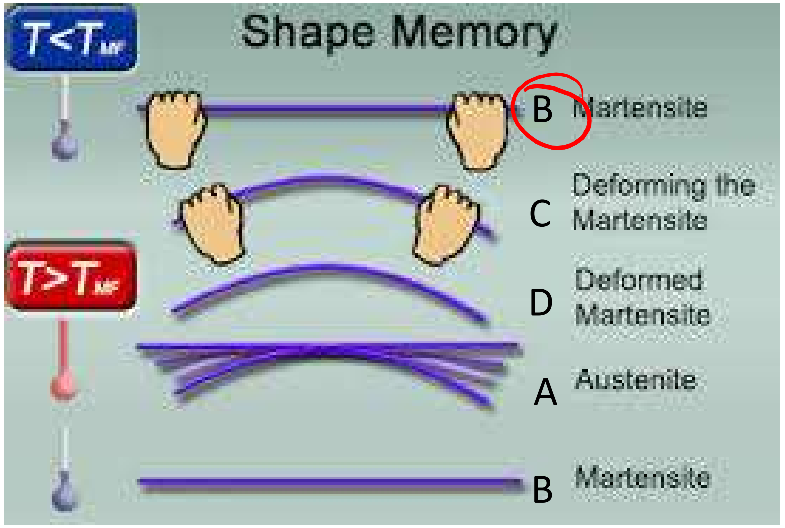
- When the alloy cools, it forms the **martensite phase** and collapses to a structure with a tetragonal crystalline structure (b).

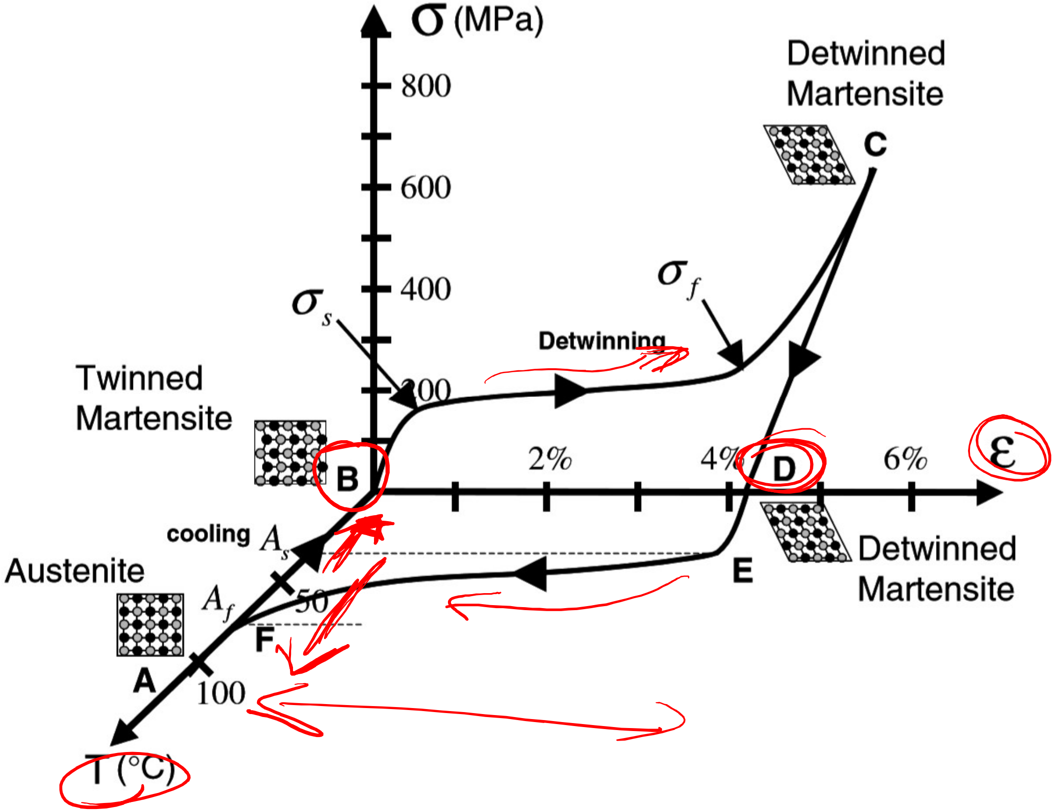
- If an *external stress* is applied, the alloy will be in **deformed martensitic phase** (c).

- Now, if the alloy is *heated again* above the transformation temperature, the austenite phase will be formed and **the structure of the material *returns to the original "cubic" form*** *(a), generating deformation and stress*.

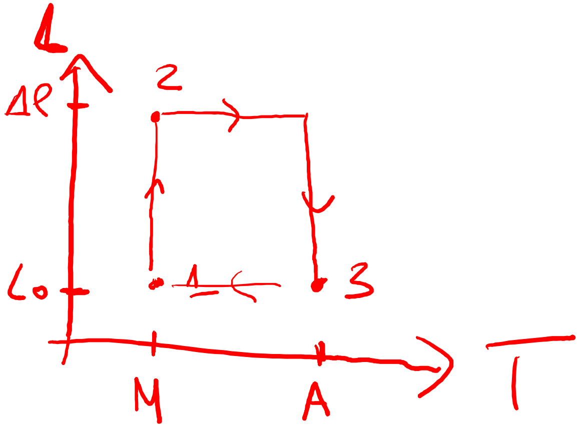
The shape memory effect (SME)

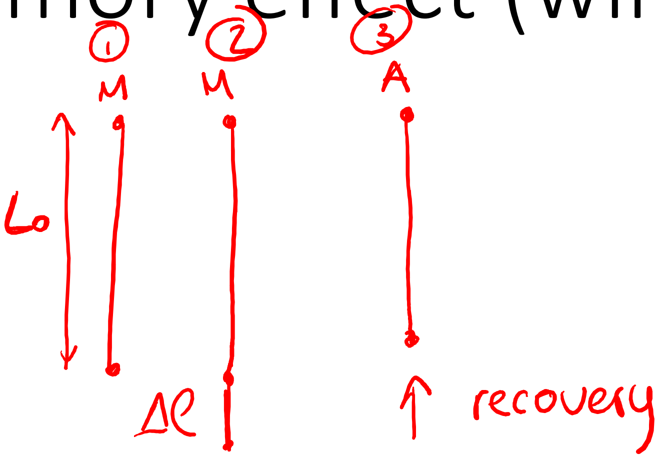
shape recovery is achieved **only during heating** *after the material in the martensitic phase been deformed by an applied mechanical load*



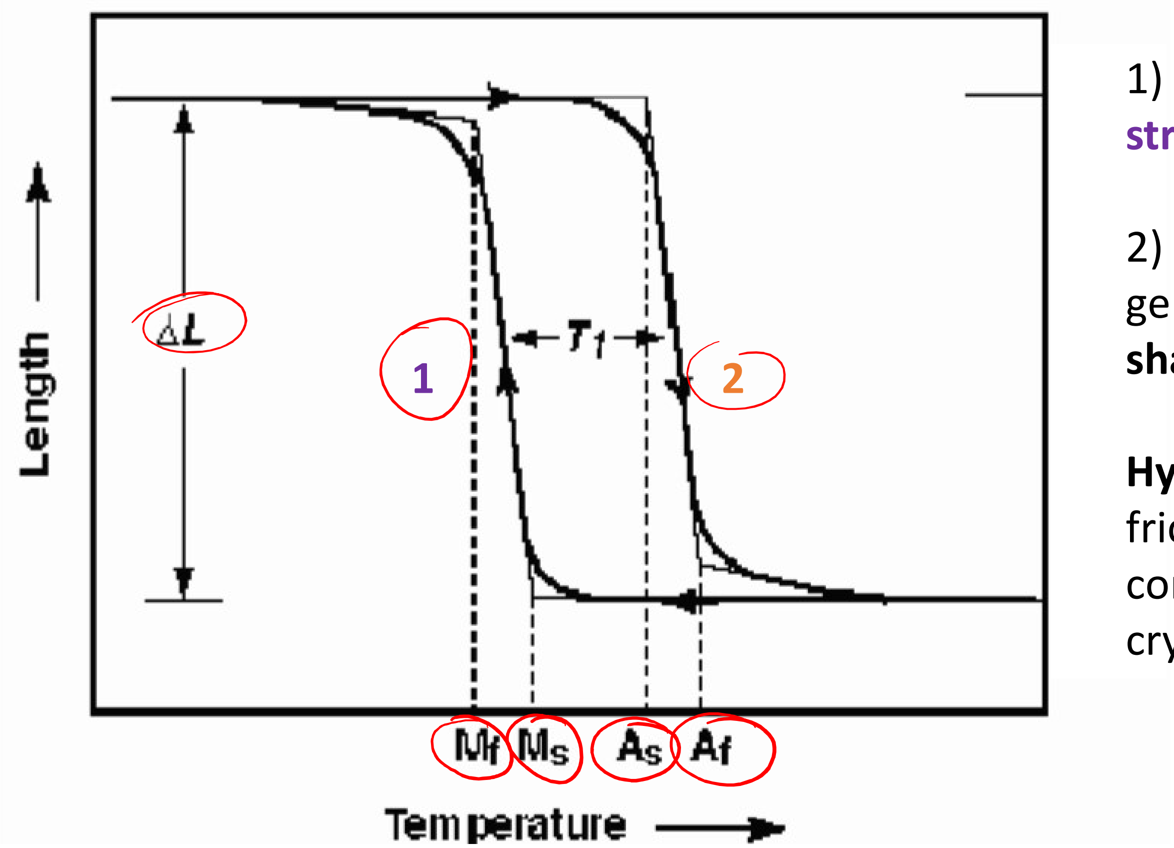


The shape memory effect (wire)





The shape memory effect (wire)

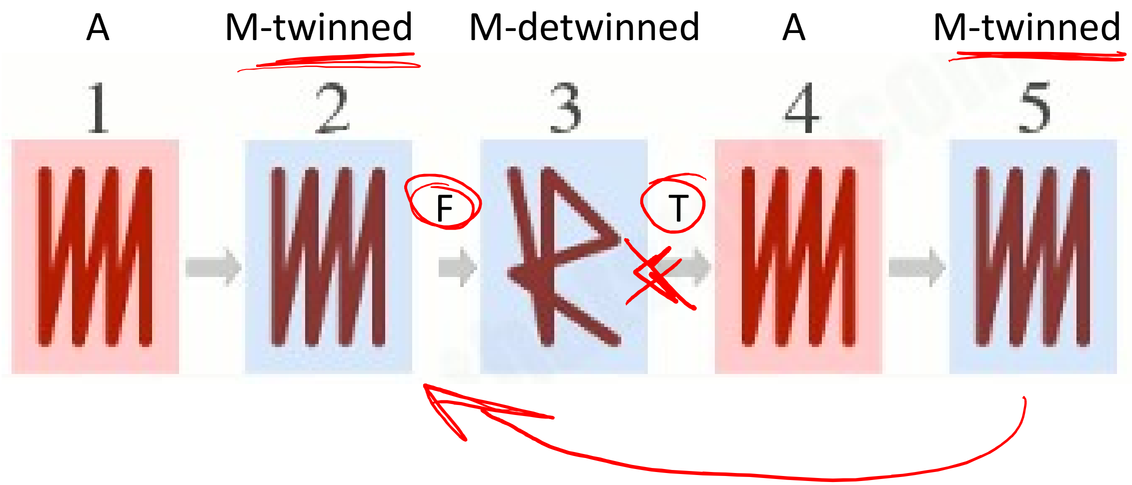


1) a wire is in the **martensite form** can be **stretched** with an external stress (dL).

2) if the wire is **heated to austenite phase**, it will generate stress and **recover the original shorter shape**.

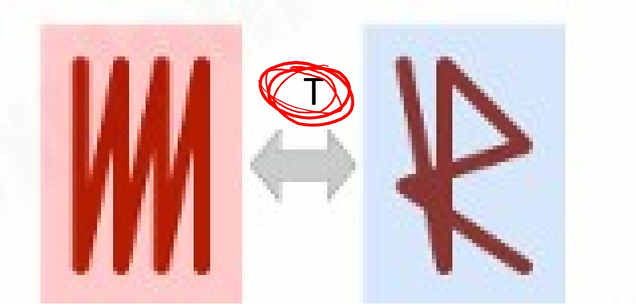
Hysteresis and non-linear behavior: Internal frictions and structural defects form as consequence of the change in the SMA crystalline structure.

One-way SME (general behaviour)



1) We "**program**" a wire by *bending it into a specific shape at a high temperature*
2) Once it's **cooled down**,
3) we can **bend it into a different form**.
4) If we *heat it above a critical temperature*, it automatically springs **back to its originally shape**.
5) If we cool it down, it stays in that shape.

Two-way SME (after ‘training’)



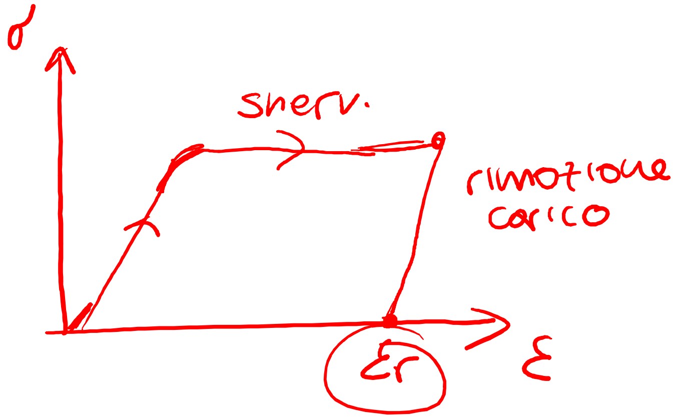
The TW-SME consists in **repeatable shape changes under no applied mechanical load** when subjected to a **cyclic thermal load**.

It can be observed in a SMA material which has undergone repeated *thermomechanical cycling along a specific loading path* (**training**) that can induce changes in the microstructure, which causes macroscopically observable permanent changes in the material behavior (M phase has a different shape of the A phase).

However, there are *limitations* that reduce the usability of the two-way effect:

- **smaller strains (2 %)** and forces
- unknown long-term fatigue and **stability** (Even slight overheating removes the SME in two-way devices).

Constitutive Model



$$\sigma = E\varepsilon + \Omega(\xi)$$

Ω ↓ trasf. fase (mat)

ξ ↓ frazione martensite

$$\sigma = E(\varepsilon - \varepsilon_r(\xi))$$

$\varepsilon_r \downarrow$ $\xi \downarrow$ $\sigma \uparrow$

$\xi = 1$

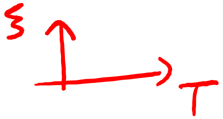
$\sigma = 0$

$\varepsilon = \varepsilon_r$

$\Downarrow$

$\Omega = -\varepsilon_r E$

Constitutive Model

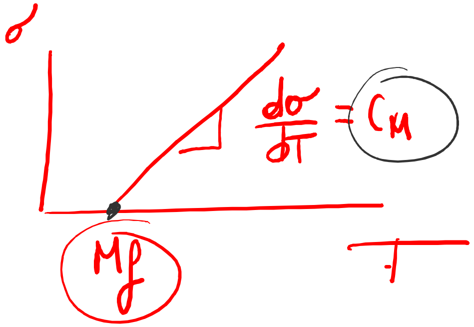


$\sigma = 0$) $\xi = \frac{1}{2}\left\{\cos\left[k_M\left(T - M_f\right)\right] + 1\right\}$ CINETICA TRASF. FASE

cost. mat
fase M

$k_M = \frac{\pi}{M_s - M_f}$

$\sigma \neq 0$)



$\frac{d\sigma}{dT} = C_M$ $\rightarrow$ $\underbrace{M_f^* = M_f + \frac{\sigma}{C_M}}$

$$\rightarrow \xi = \frac{1}{2}\left\{\cos\left[k_M\left(T - \underbrace{M_f - \frac{\sigma}{C_M}}_{M_f^*}\right)\right] + 1\right\}$$

$\uparrow$

NITINOL $M_s = 23^\circ C$ $M_f = \boxed{5^\circ C}$ $C_M = 11.3\ MPa/^\circ C$

a) ξ @ $\boxed{15^\circ C}$ $(\underline{\sigma = 0})$

$$\xi = \frac{1}{2}\left\{\cos\left[k_M\left(T - \boxed{M_f}\right)\right] + 1\right\} =$$

$$k_M = \frac{\pi}{M_s - M_f} = \frac{\pi}{23^\circ C - 5^\circ C} = 0.175\ ^\circ C^{-1}$$

$$= \frac{1}{2}\left\{\cos\left[0.175\ \frac{1}{^\circ C}\left(15^\circ C - 5^\circ C\right)\right] + 1\right\} = \underline{0.411}$$

b) Tcost @ 23 °C , ξ @ $\underline{90\ \text{MPa}}$

$$\xi = \frac{1}{2}\left\{\cos\left[K_M\left(T - M_f - \frac{\sigma}{C_M}\right)\right] + 1\right\}$$

$$= \frac{1}{2}\left\{\cos\left[0.175\,\frac{1}{\cancel{^\circ C}}\left(23\cancel{^\circ C} - 5\cancel{^\circ C} - \frac{90\ \text{M}\cancel{\text{Pa}}}{11.3\ \text{M}\cancel{\text{Pa}\,^\circ C^{-1}}}\right)\right] + 1\right\} = \underline{0.612}$$

Superelasticity (SE)

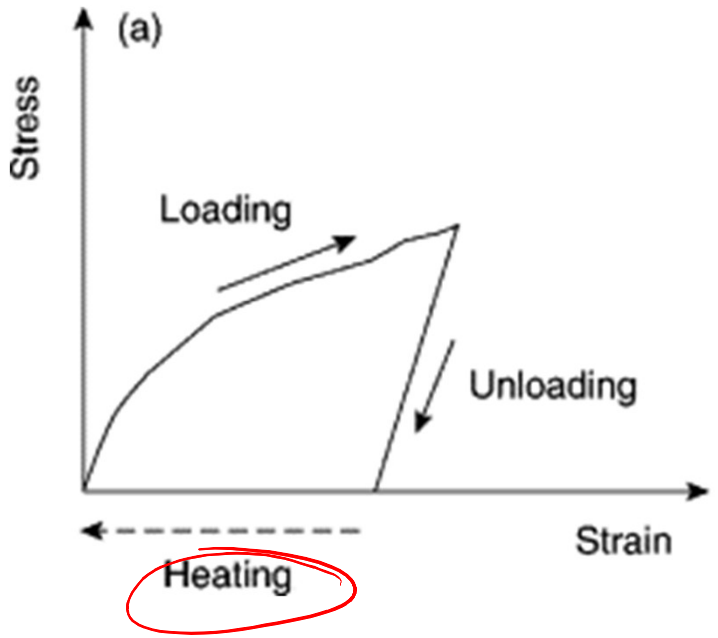
This effect is caused by the **stress-induced formation of martensite** above its normal temperature.

The martensite **reverts immediately to undeformed austenite as soon as the stress is removed**.
This process provides a very springy, "rubberlike" elasticity in these alloys.

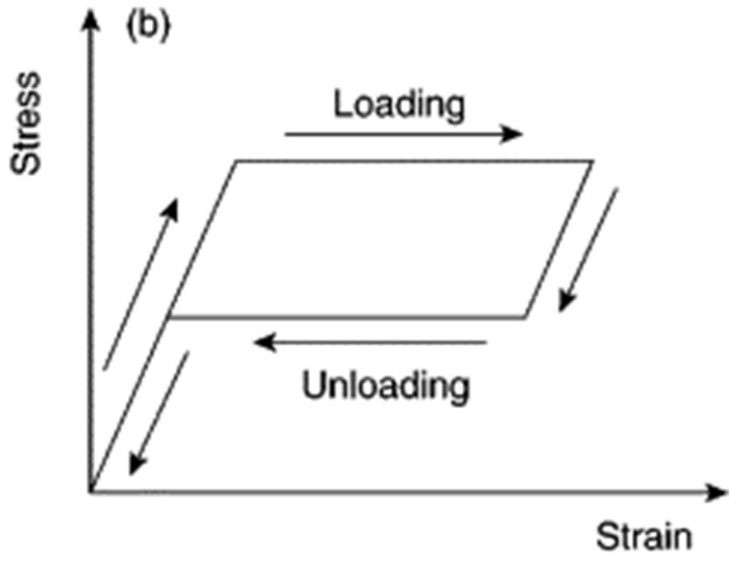
However, the superelastic behaviour is not usable in actuators. As an example, the superelastic alloys are used in eyeglass frames.

Figure 3: DuraFLEX eyeglasses.

Shape memory effect vs. Superelasticity

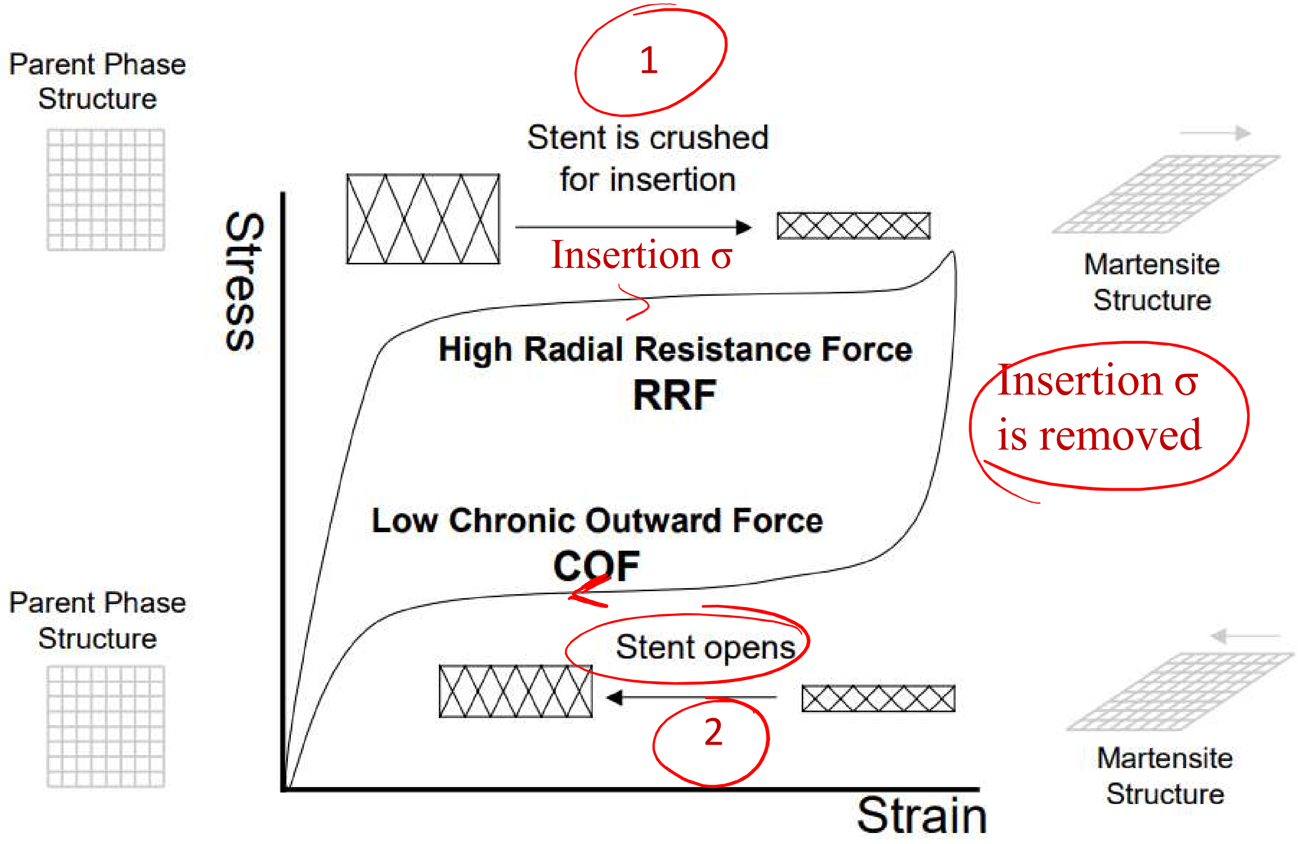


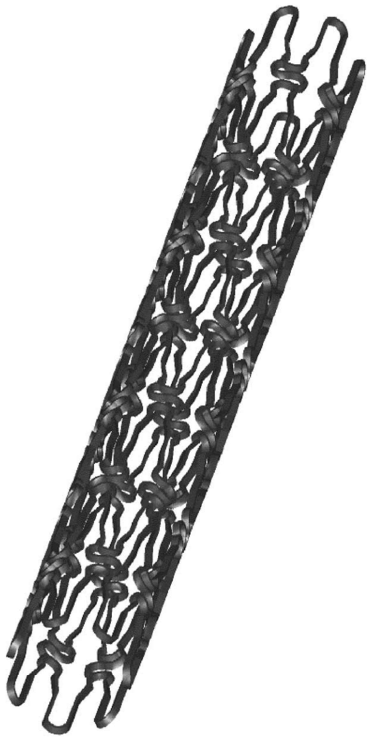
In ***SME***, a previously deformed alloy can be made to **recover its original shape simply by heating**;



while in ***SE***, the alloy can be bent or stretched to a great extent, but **returns to its original shape once the load is released.**

Example of SE Application: vascular stent

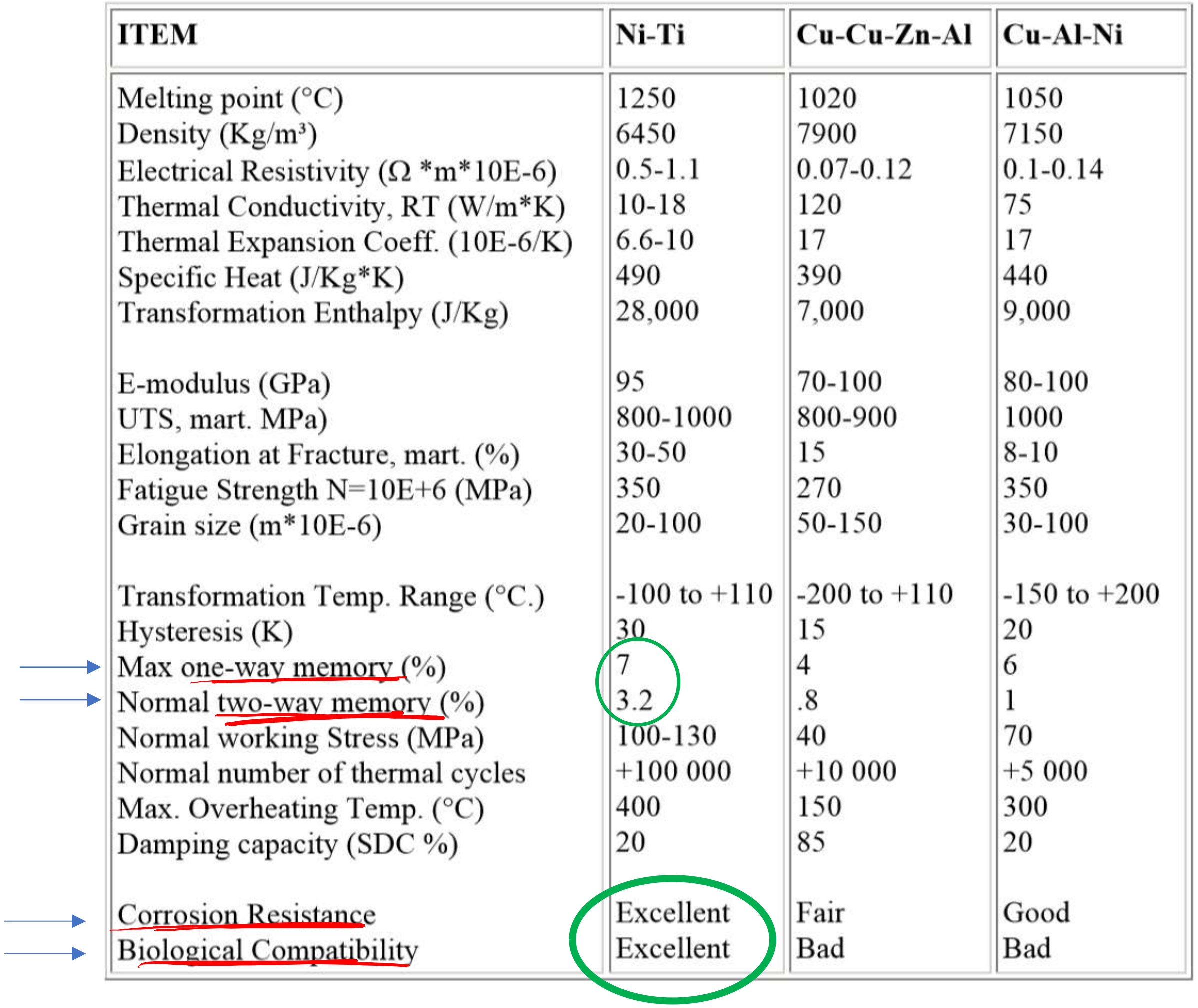




The chronic stress on the vessel (2) will be lower than insertion stress (1)

Examples of Shape Memory Alloys

Nitinol (Nichel Titanium Naval Ordinance Laboratory)



ITEM	Ni-Ti	Cu-Cu-Zn-Al	Cu-Al-Ni
Melting point (°C)	1250	1020	1050
Density (Kg/m^3)	6450	7900	7150
Electrical Resistivity (Ω *m*10E-6)	0.5-1.1	0.07-0.12	0.1-0.14
Thermal Conductivity, RT (W/m*K)	10-18	120	75
Thermal Expansion Coeff. (10E-6/K)	6.6-10	17	17
Specific Heat (J/Kg*K)	490	390	440
Transformation Enthalpy (J/Kg)	28,000	7,000	9,000
E-modulus (GPa)	95	70-100	80-100
UTS, mart. MPa)	800-1000	800-900	1000
Elongation at Fracture, mart. (%)	30-50	15	8-10
Fatigue Strength N=10E+6 (MPa)	350	270	350
Grain size (m*10E-6)	20-100	50-150	30-100
Transformation Temp. Range (°C.)	-100 to +110	-200 to +110	-150 to +200
Hysteresis (K)	30	15	20
Max one-way memory (%)	7	4	6
Normal two-way memory (%)	3.2	.8	1
Normal working Stress (MPa)	100-130	40	70
Normal number of thermal cycles	+100 000	+10 000	+5 000
Max. Overheating Temp. (°C)	400	150	300
Damping capacity (SDC %)	20	85	20
Corrosion Resistance	Excellent	Fair	Good
Biological Compatibility	Excellent	Bad	Bad

Recent Patents on Biomedical Engineering **2008, *1*, 180-196**

Enhanced Nitinol Properties for Biomedical Applications

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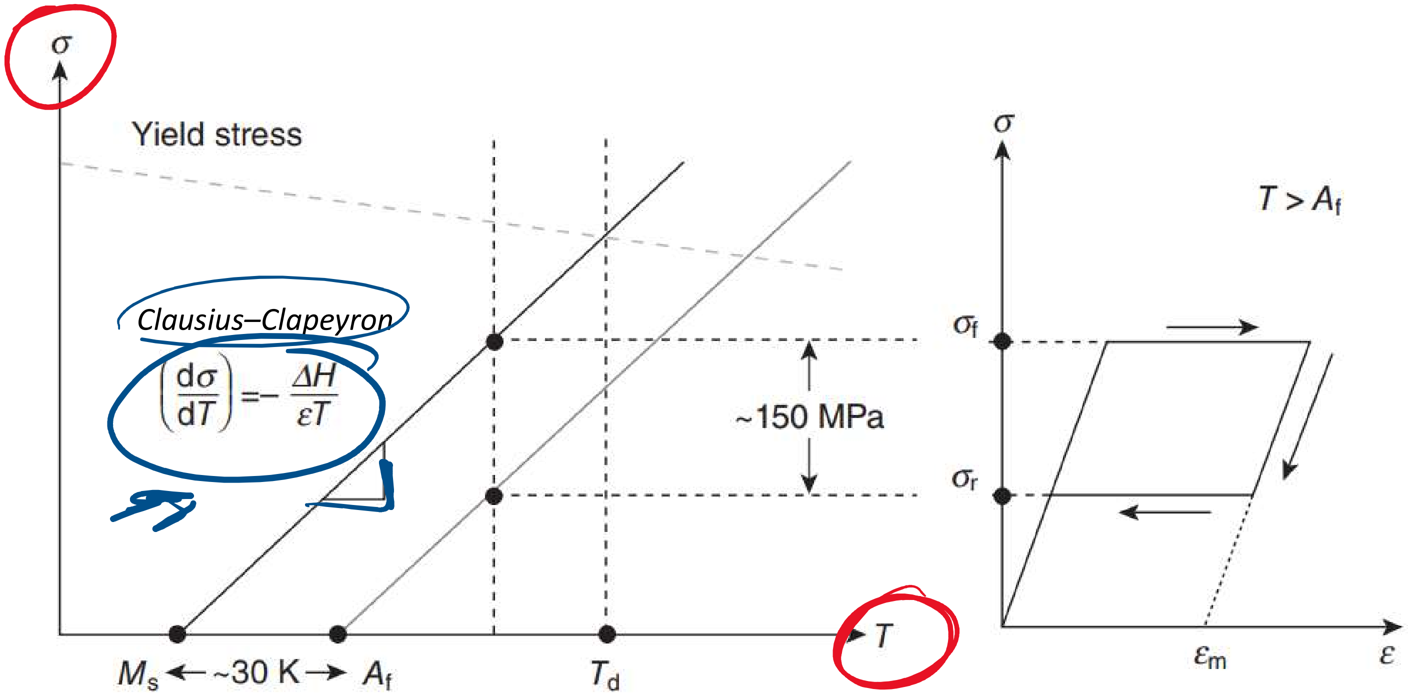
Abstract: In recent years, Nitinol producers and medical products have experienced an exponential growth, driven by advanced manufacturing techniques and the use of progressively less invasive medical procedures. Concurrently, new processing techniques have been developed to further enhance the valuable properties of Nitinol used in medical devices; recent patents on these techniques include changing the composition of nickel and titanium, alloying the nickel-titanium with other elements, improving melting practices, heat-treating the alloy, and mechanical processing of the alloy. For example, alloying the nickel-titanium with ternary elements may widen the superelastic temperature operating window, maximize/minimize the stress-strain hysteresis, and improve the radiopacity of a Nitinol intraluminal device comparable to that of a stainless steel device of the same strut pattern coated with a thin layer of gold. Limiting to less than 30% the final cold work step (after a full anneal, and before the shape-setting step) may improve the Nitinol fatigue lifetime of about 37%, the fatigue lifetime being a primary factor limiting the performances of Nitinol endoluminal prosthetic implants. Local selective and differential thermo-mechanical treatments have also been devised to achieve different physical properties in different portions of a Nitinol medical device in order to improve its performance under expected operating conditions.

Keywords: Nitinol, NiTi, titanium, nickel, NiTi based alloys, superelastic, superelaticity, shape memory, processing, fatigue, hysteresis, radiopacity.

Clausius-Clapeyron equation



Temperature dependence of transformation stress.

(The stress required to induce the transformation increases linearly with temperature)

$$E^{a}_{gibbs} = H^{a} - T S^{a}$$

entalpia

entropia

$$E^{m}_{gibbs} = H^{m} - T S^{m}$$

$$\Delta G^{am} = \Delta H^{am} - T\Delta S^{am} - \boxed{\sigma \varepsilon V}$$

$$[J] \quad [J] \quad [\cancel{K}]\left[\frac{J}{\cancel{K}}\right] \quad \left[\frac{N}{m^2}\, m^3\right] J$$

$$\Delta G^{am}_{v} = \underbrace{\frac{\Delta H^{am}}{V}}_{\Delta H^{am}_{v}} - \underbrace{\frac{T\Delta S^{am}}{V}}_{\Delta S^{am}_{v}} - \frac{\sigma \varepsilon \cancel{V}}{\cancel{V}}$$

$$\sigma = \frac{\Delta H^{am}_{v} - T\Delta S^{am}_{v}}{\varepsilon} \Rightarrow \boxed{\frac{d\sigma}{dT} = -\frac{\Delta S^{am}_{v}}{\varepsilon} = -\frac{\Delta H^{am}_{v}}{T\varepsilon}}$$

$$\underline{\Delta G = 0} \qquad \Delta G = \Delta H - T\Delta S = 0 \Rightarrow \boxed{\Delta S = \frac{\Delta H}{T}} \Leftarrow$$

SMA actuators

SMA elements can only provide **force/displacement only in one direction**. Thus, a **bias (return) mechanism** is necessary:

1. **Gravity:** the **load force has to be large enough** at all times, otherwise the actuator remains in the austenite position, even if heating is deactivated.

2. **conventional spring:** the **net output force decreases**, because the force of the bias mechanism opposes the force of the SMA element.

3. **antagonistic SMA**: provides **output force to both directions**, but the **heating and cooling of opposing elements must be arranged properly**. For example, if the elements are very close to each other, the heat transfer between elements can generate undesired forces.

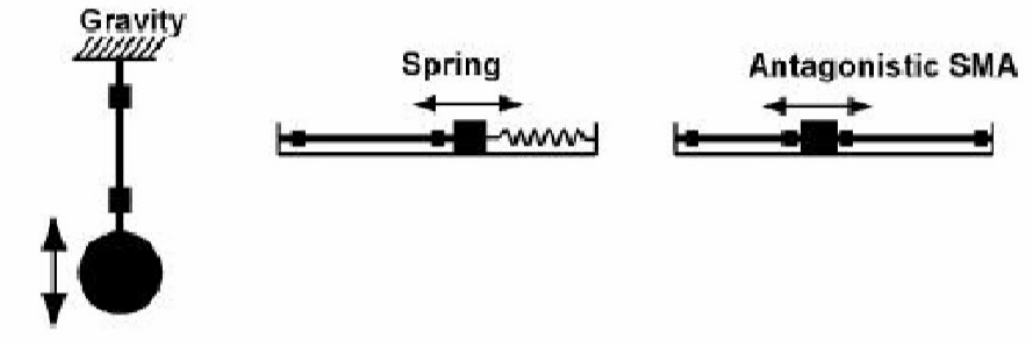
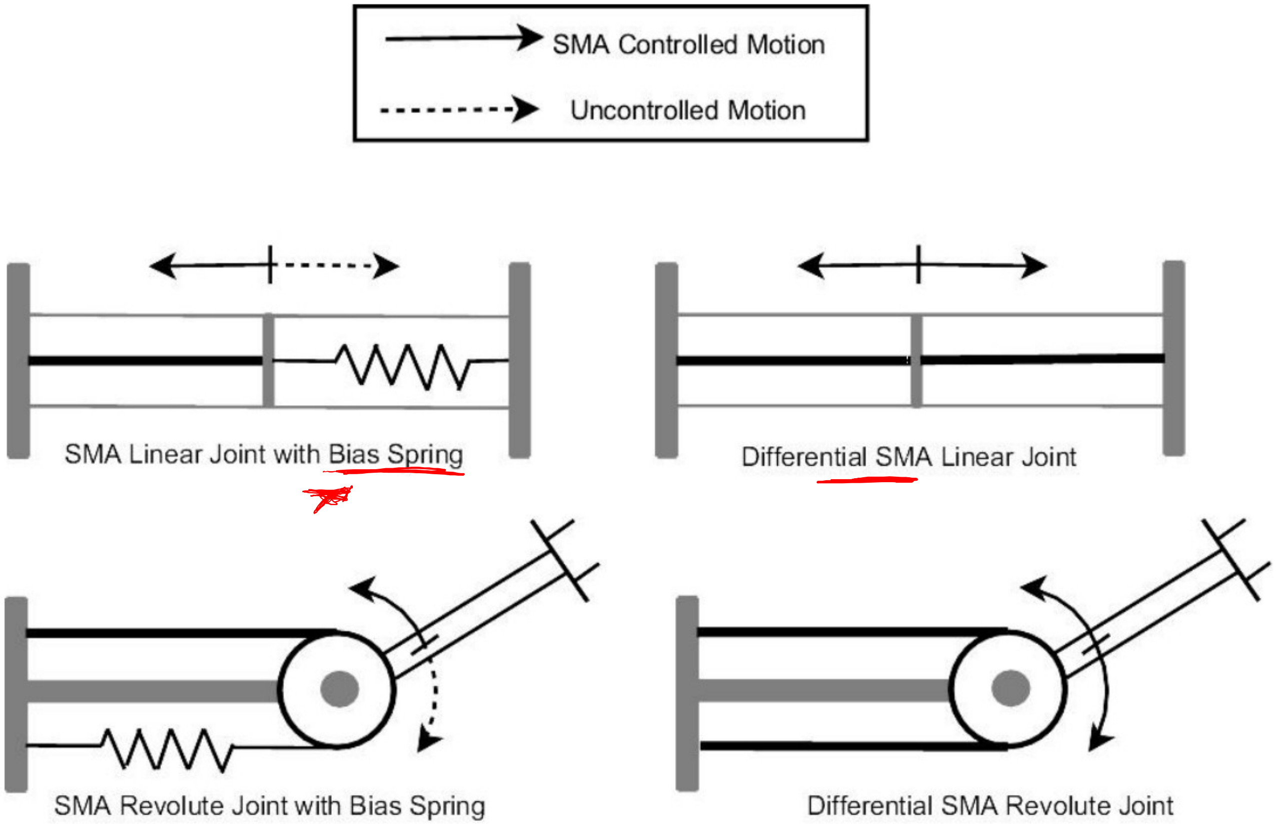


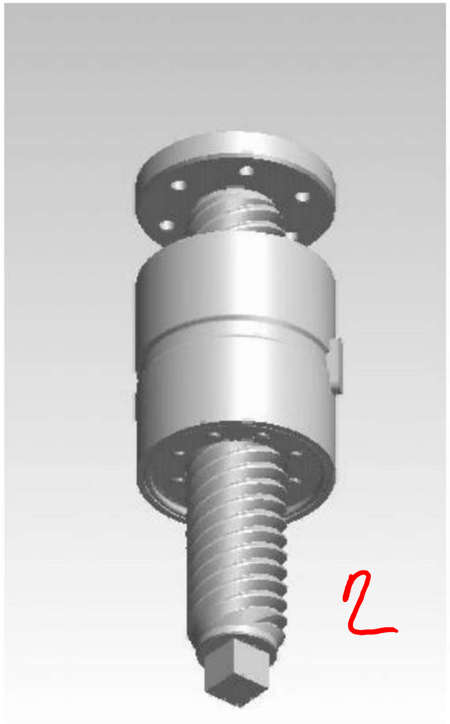
Figure 4: Bias mechanisms in SMA actuators.

SMA Actuators (2)



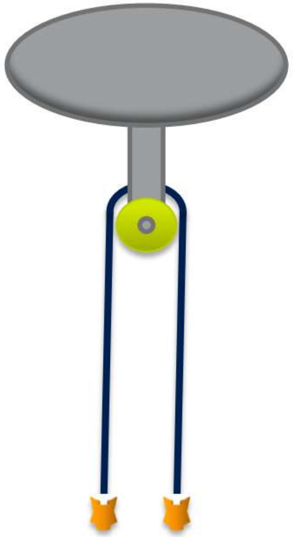
Advantages of SMA in linear actuators

Traditional Approach



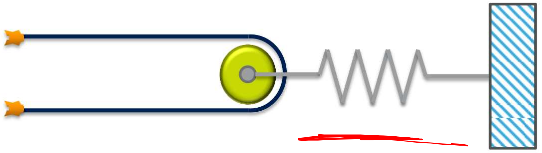
2

SMA Approach

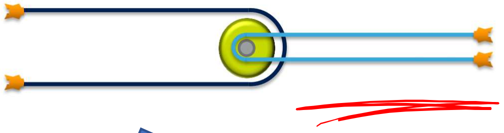


SMA-wire diameter [µm]	Max Force [N]	Max Stroke	Suggesting operating Force [N]	Suggested operating Stroke
25	0.3	5%	0.1	<3,5%
50	1.2		0.3	
100	4.7		1.3	
150	6.2		2.7	

Spring
as counterforce
(no control)



Second Wire
as counterforce
(fully controlled)



Pro:

- The movement is really linear
- The system is silent
- The SMA wire does not occupy space

Con:

- One direction with one wire (a counter force is needed)

SMA Actuators - Driving

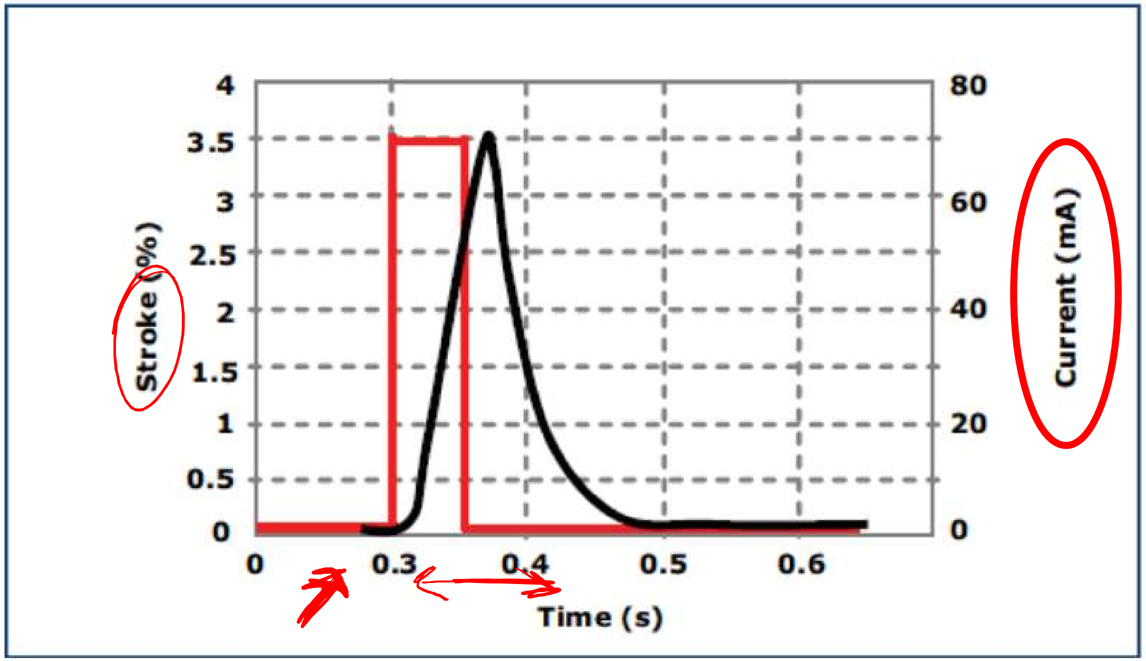
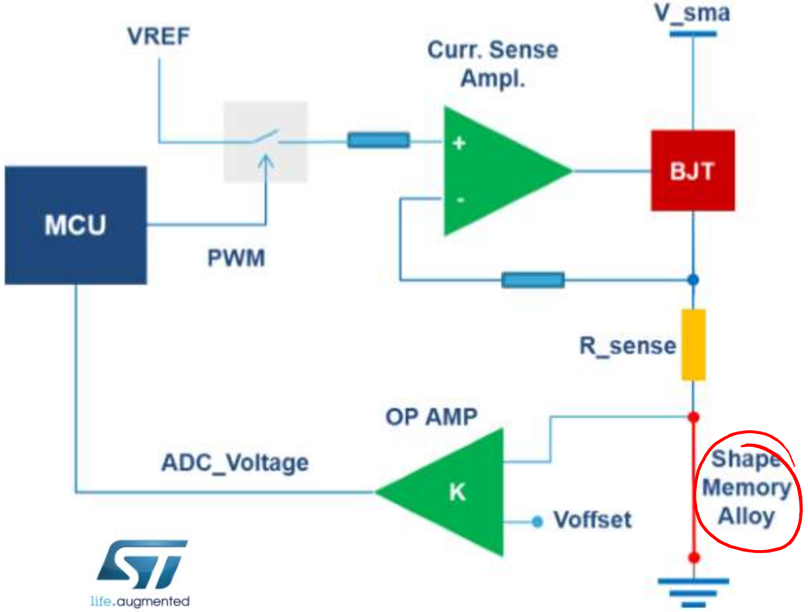


Figure 2. Stroke vs. Time [1st cycle, L=100mm, T=25°C, Max Curr.=70mA, Max Stress= 170 MPa] (Courtesy of SAES Getters)



SMA Actuators – Feedback signal

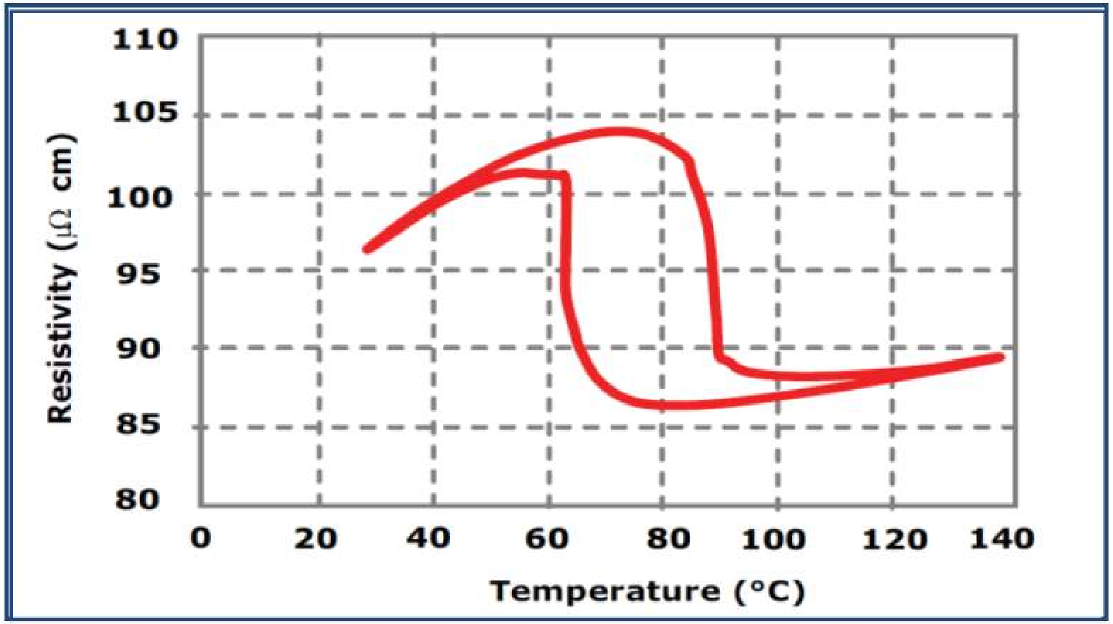


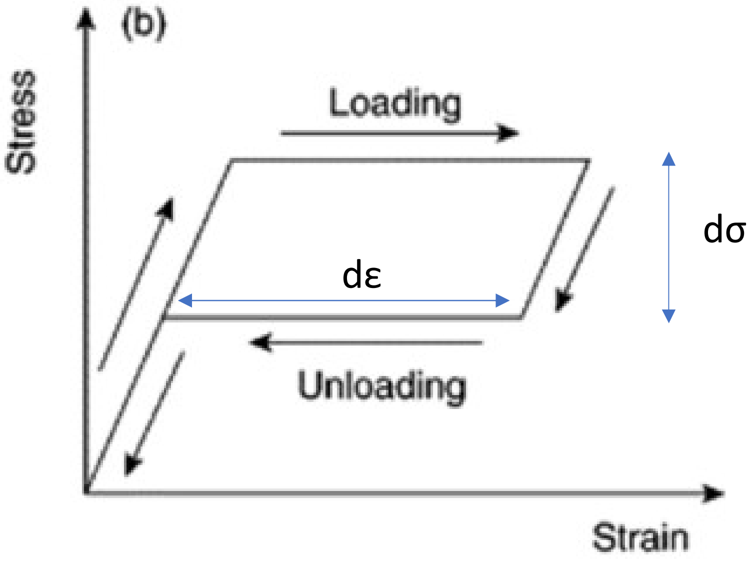
Figure 1. Resistivity of the material changes during martensitic transformation showing the hysteresis curve behavior. (Courtesy of SAES Getters)

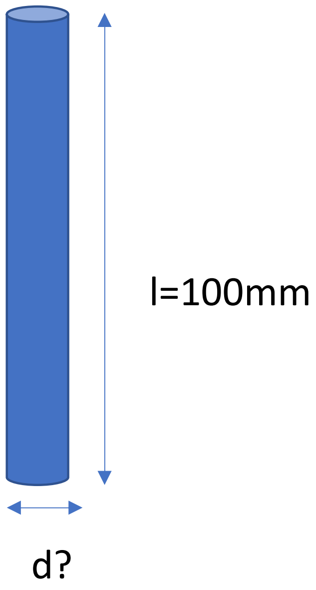
The **electrical resistance of the material changes** during the cooling process of the martensitic transformation, and during the heating process on the reverse transformation.

This characteristic is fundamental for implementing a new actuator family where the **position feedback is directly retrieved by the SMA resistance values**.

Esercizi

1. Considerando la seguente curva per un materiale superelastico filiforme che durante un ciclo svolge un lavoro di 5.8 mJ, calcolare che diametro dovrà avere il filo ($d\sigma$= 150 MPa, $d\varepsilon$=5%, l=100mm)





2. Considerando il filo precedente, noto il lavoro svolto durante il ciclo, calcolare la potenza considerando di svolgere il ciclo in 1 min.

$$W = \sigma \varepsilon \boxed{V} \Rightarrow V = \frac{W}{\sigma \varepsilon} = \frac{5.8\,mJ}{150\,e^{6} \times 0.05} = 7.73\,e^{-10}\,m^3$$

$$V = \pi r^2 \underbrace{\ell} \Rightarrow r = \sqrt{\frac{V}{\pi \ell}} = \sqrt{\frac{7.73\,e^{-10}}{3.14 \times 100\,e^{-3}}} = 49.6\,e^{-6}\,m$$

$$\simeq 50\,\mu m$$

$$d = 100\,\mu m$$

$$P = \frac{W}{t} = \frac{5.8\,mJ}{1\,\cancel{min} \cdot 60\,s / \cancel{min}} = 96.67\,\mu W$$