



COM783 – Mecânica de Sistemas Inteligentes: Materiais Inteligentes e Suas Aplicações

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Universidade Federal do Rio de Janeiro (COPPE/UFRJ)

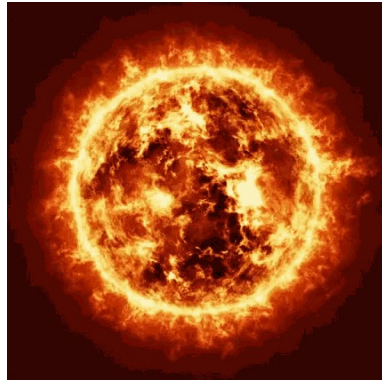
Programa de Engenharia Mecânica (PEM)

Materiais Inteligentes: Acomplamento Multifísico

Mecânico



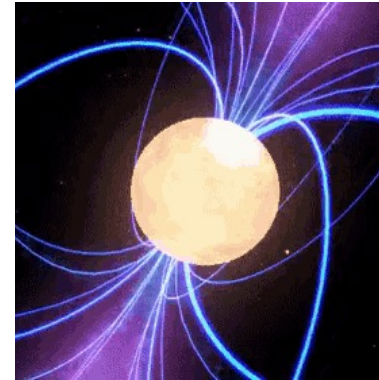
Térmico



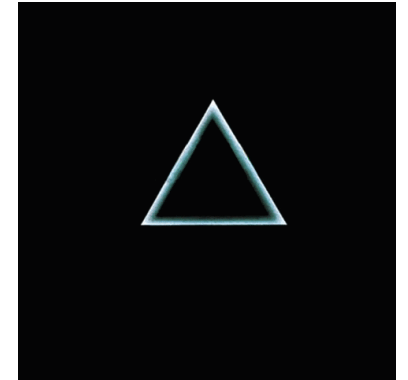
Elétrico



Magnético



Óptico



Shape Memory Alloys (SMAs)

Shape Memory Polymers (SMPs)

Efeito Memória de Forma

William J Buheler (1923 – 1889)



Liga de Níquel-Titânio, “*Nitinol*” (1962)



Materiais com Memória de Forma

Ligas NiTi (Nitinol)



Ligas Cu-Zn-Al



Ligas Cu-Al-Ni



Poliuretanos (PUs)



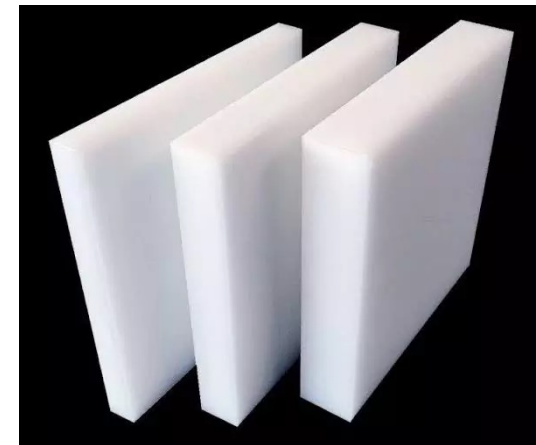
Ácido Polilático (PLA)



Ácido Poli(metacrílico) (PMAA)

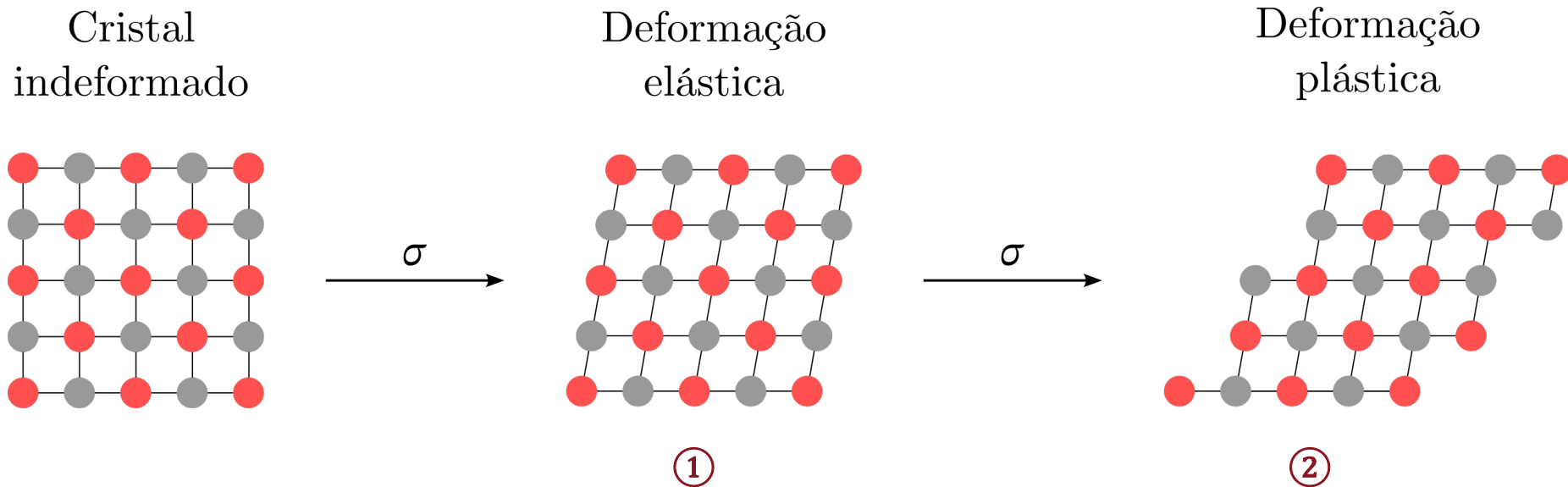


Polietileno (PE)



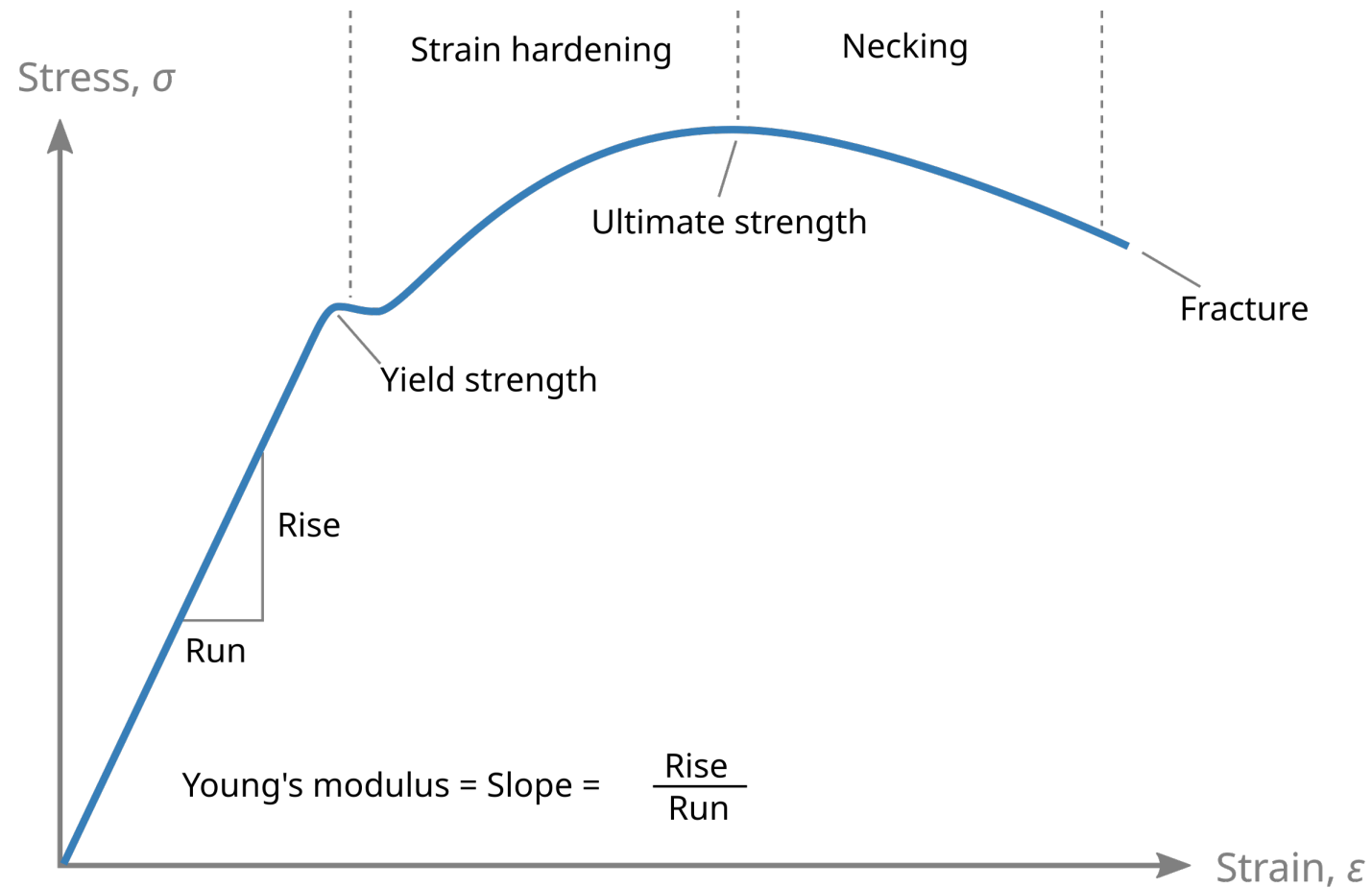
Ligas com Memória de Forma (SMAAs)

Deformação em Ligas Convencionais



- ① Distorção através do estiramento das ligações (reversível)
- ② Distorção através de um rearranjo das ligações (irreversível e dissipa energia)

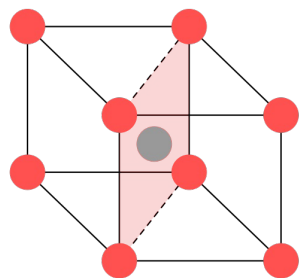
Deformação em Ligas Convencionais



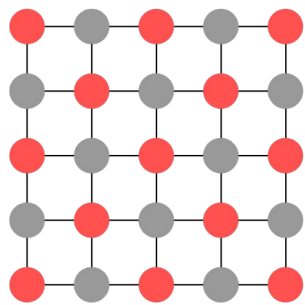
Deformação em Ligas com Memória de Forma

→ Mecanismo de transformação de fase tipo sólido-sólido

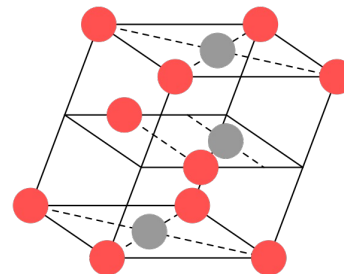
Austenita



Estável em alta temperatura

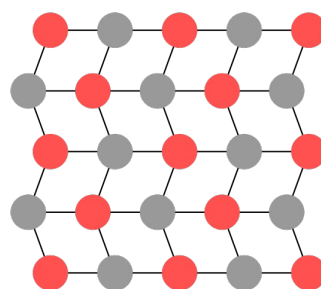


Martensita

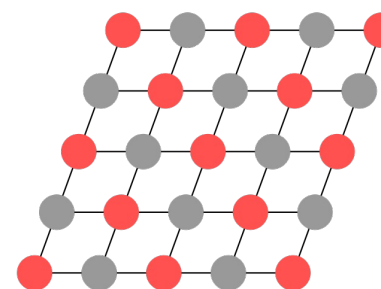


Estável em baixa temperatura

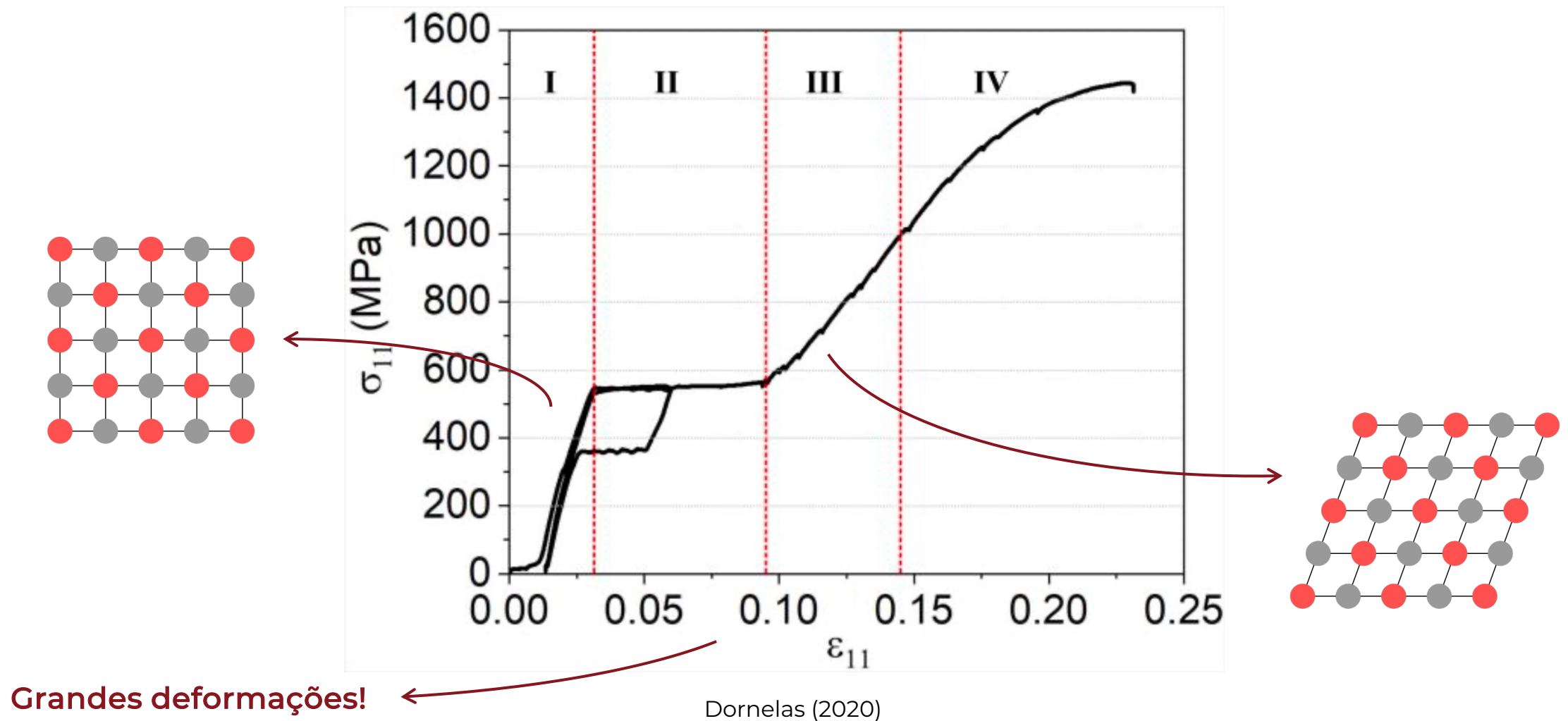
Maclada



Demaclada



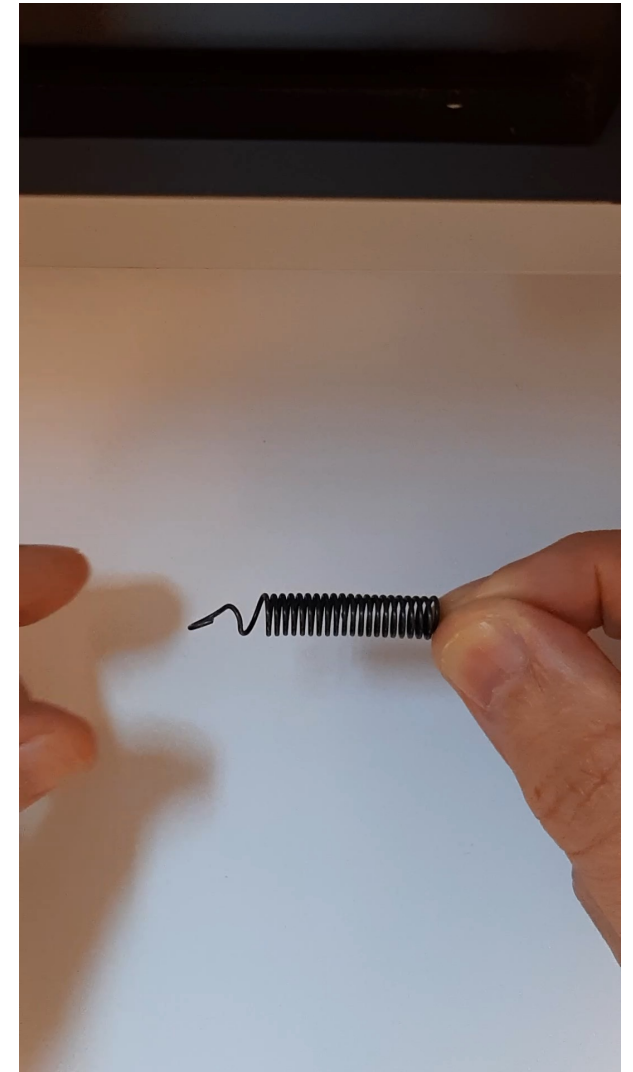
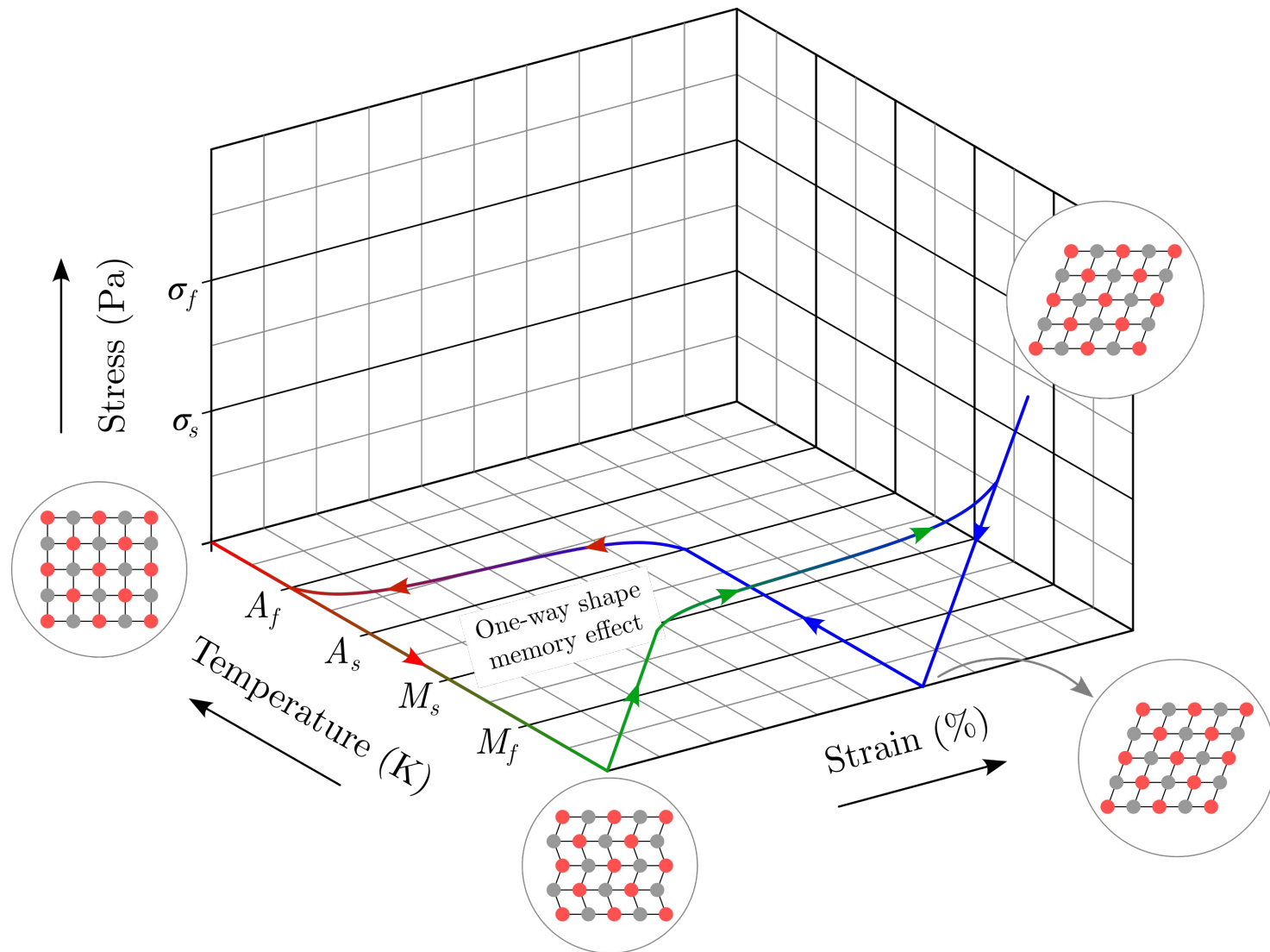
Deformação em Ligas com Memória de Forma



Efeitos Termomecânicos em Ligas SMA

- Efeito Memória de Forma (One-Way)
- Efeito Pseudoelástico
- Transformação de Fase Induzida por Temperatura
- Efeito Memória de Forma Bidirecional (Two-Way)
- Assimetria Tensão-Compressão
- Plasticidade Induzida por Transformação de Fase
- ...

Efeito Memória de Forma



Efeito Pseudoelástico (Superelástico)

Brass

Plastic Buckling & Fracture



Stainless Steel

Plastic Deformation

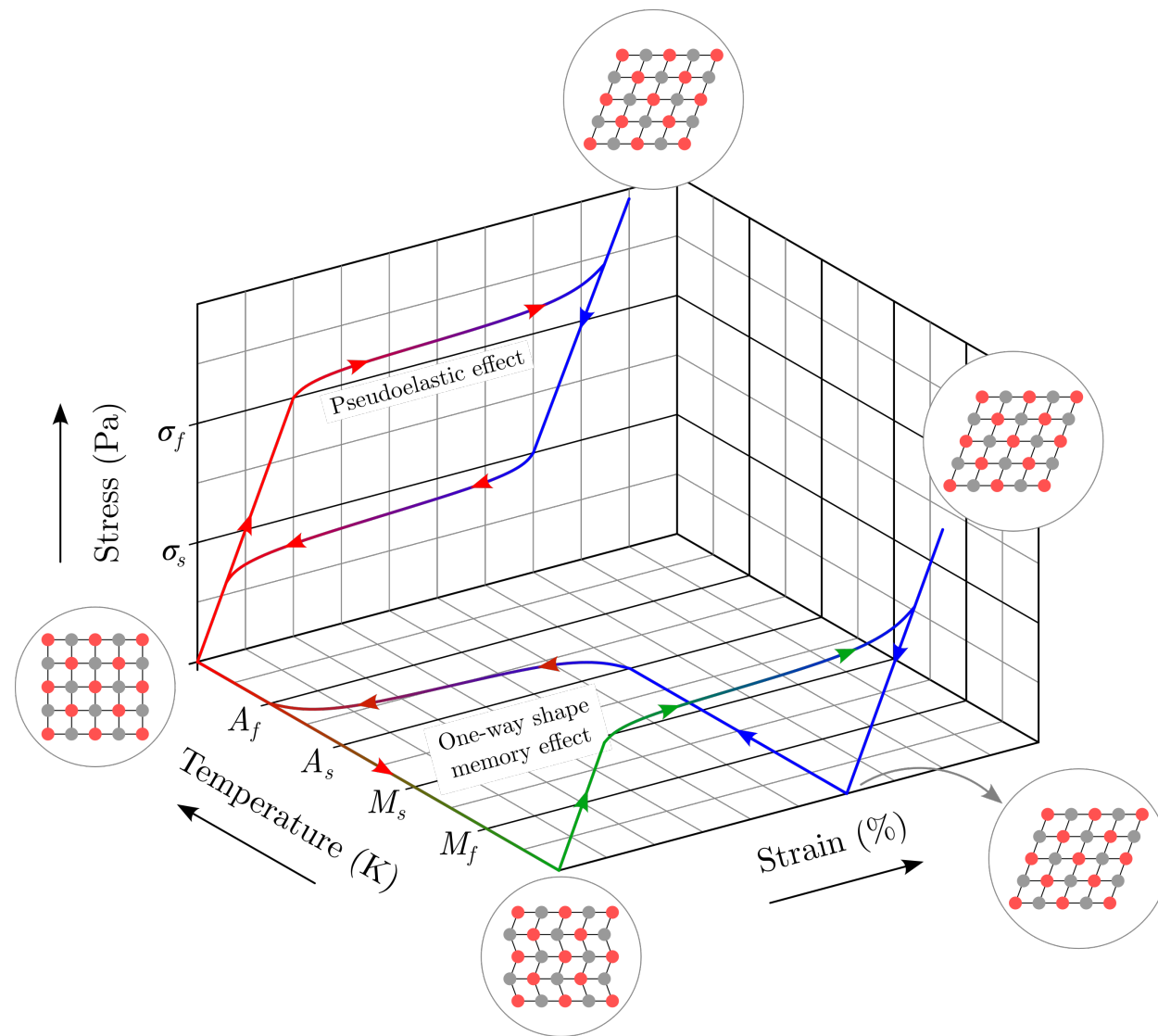


Shape Memory Alloy

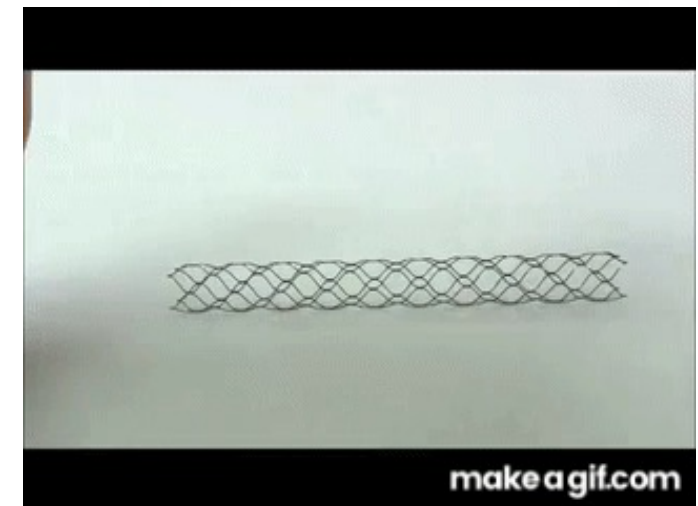
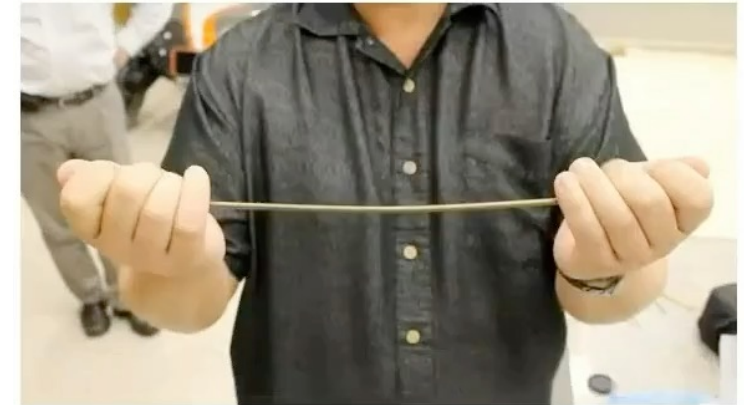
Reversible Pseudoelasticity



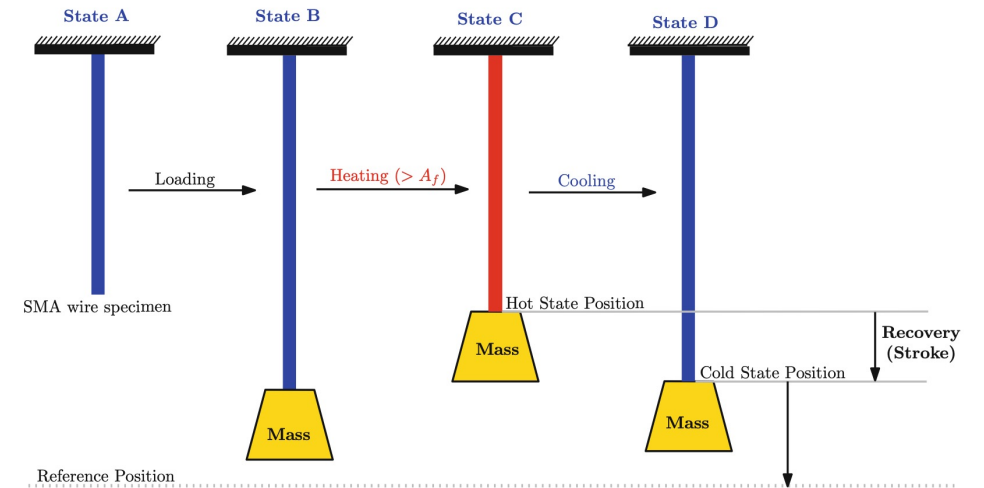
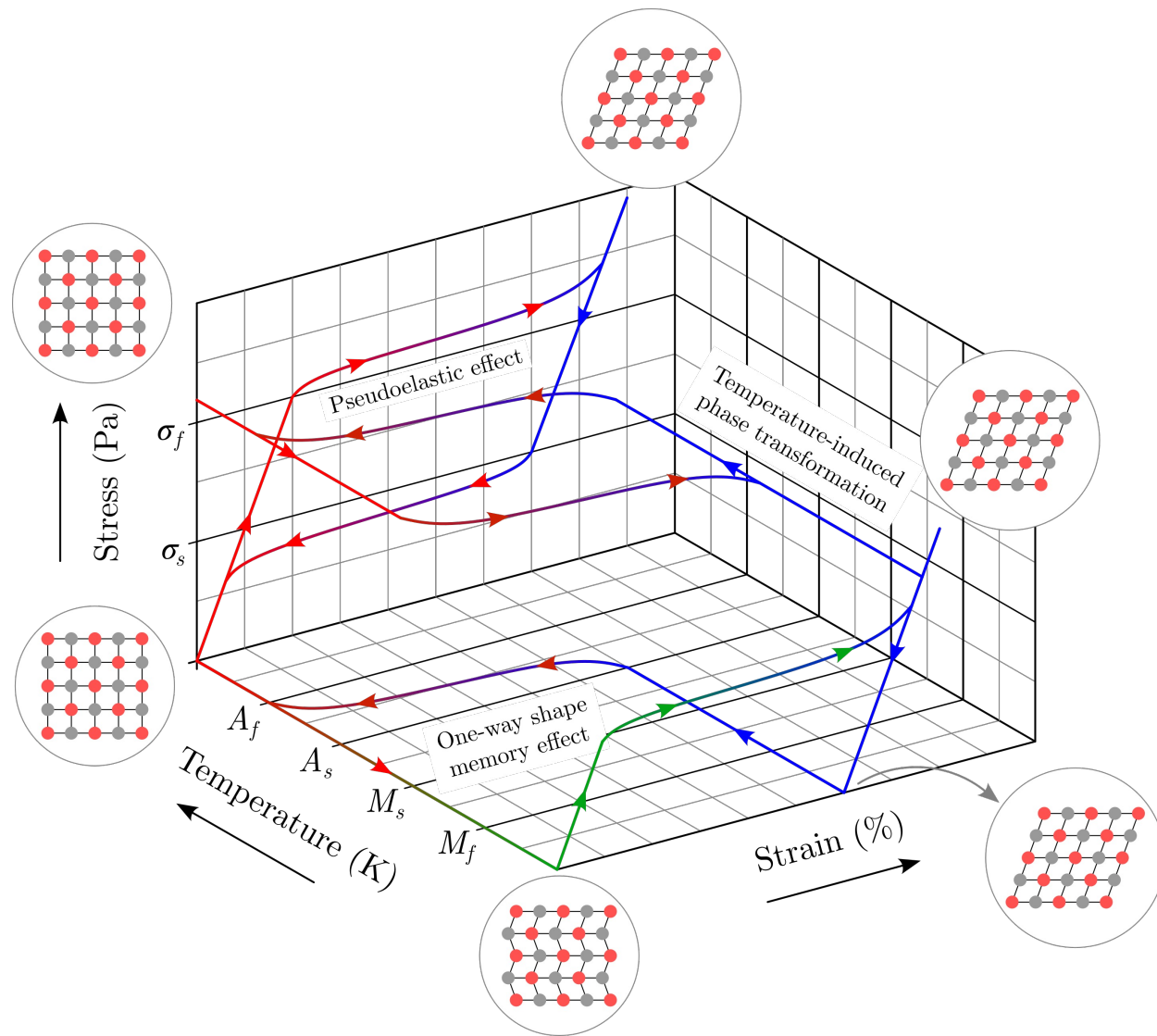
Efeito Pseudoelástico (Superelástico)



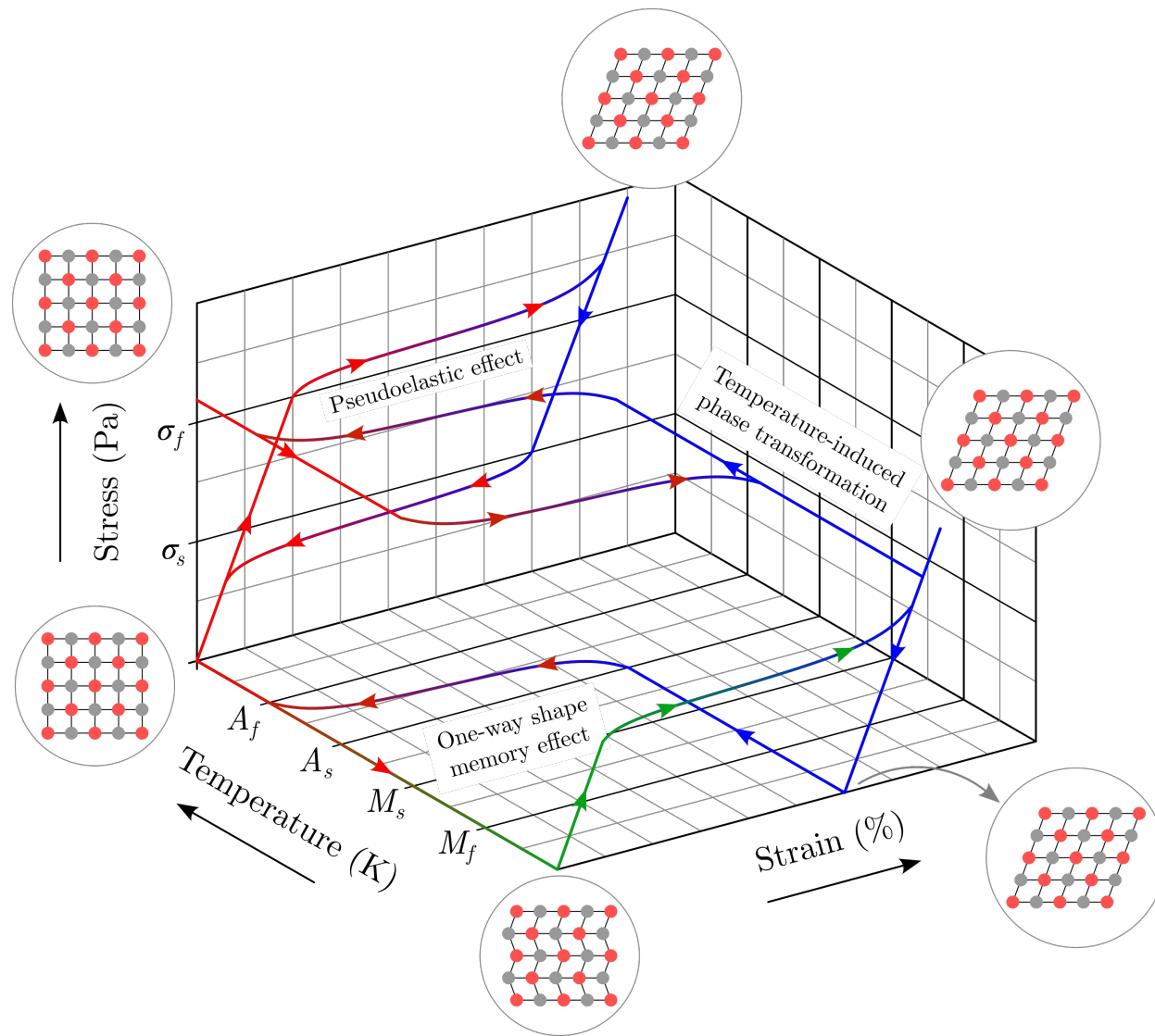
Shape Memory Alloy
Reversible Pseudoelasticity



Transformação de Fase Induzida por Temperatura



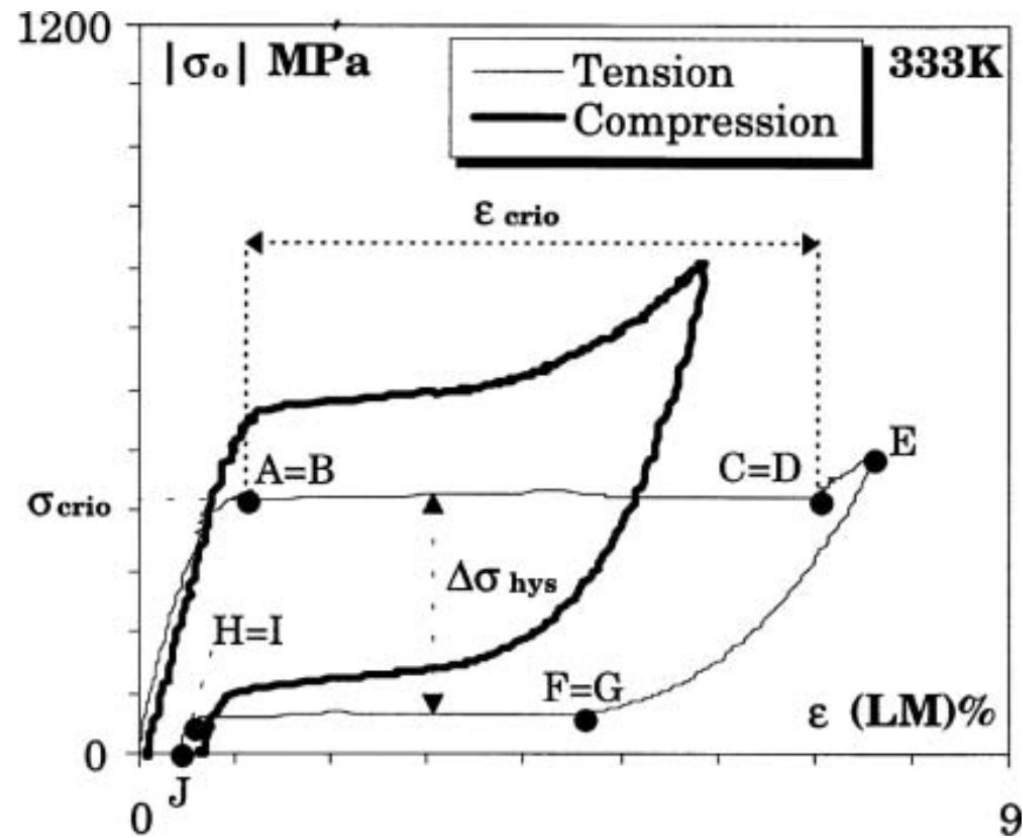
Transformação de Fase Induzida por Temperatura



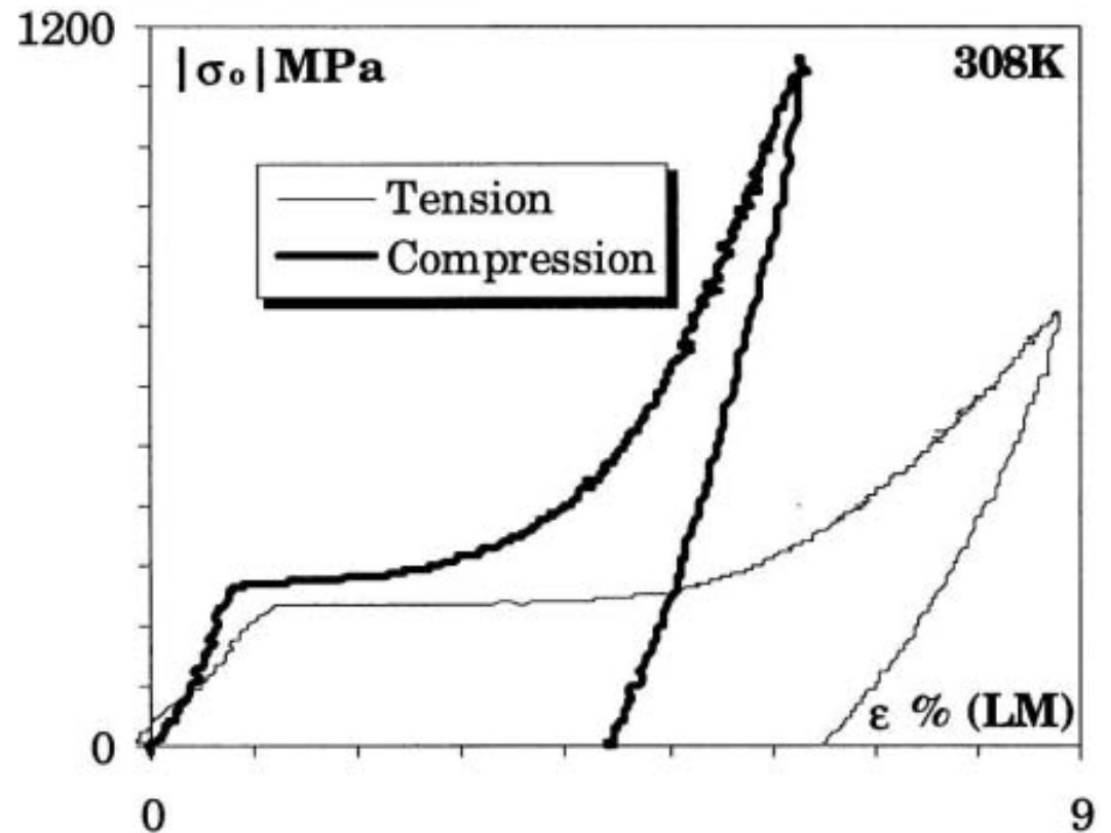
- Two-Way Shape Memory Effect (Bidirecional) se tensão for residual
- Feita por treinamento (repetição de estímulos específicos diversas vezes)

Assimetria Tensão-Compressão

Liga Pseudoelástica

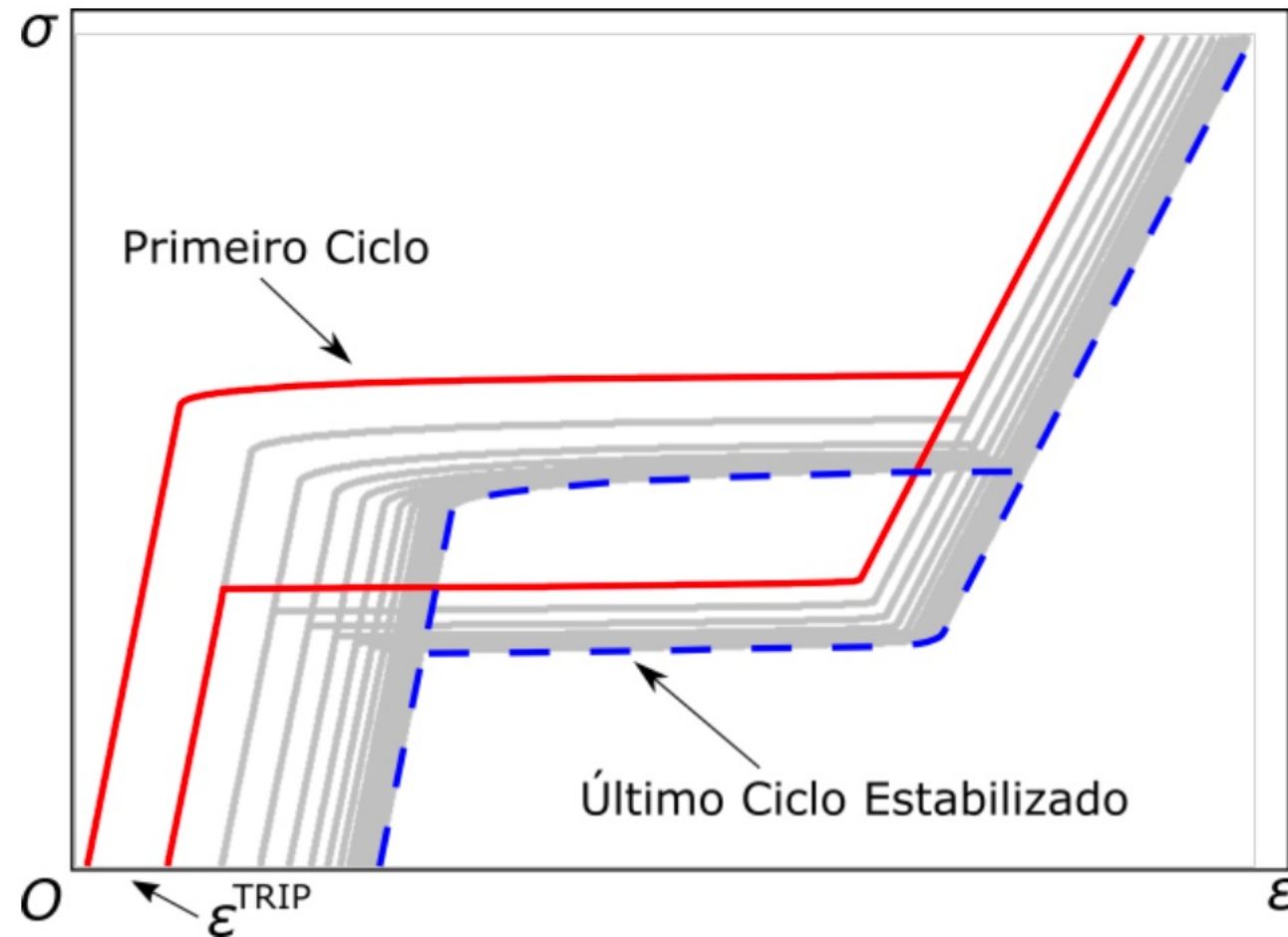


Liga Martensítica



Orgéas & Favier (1998)

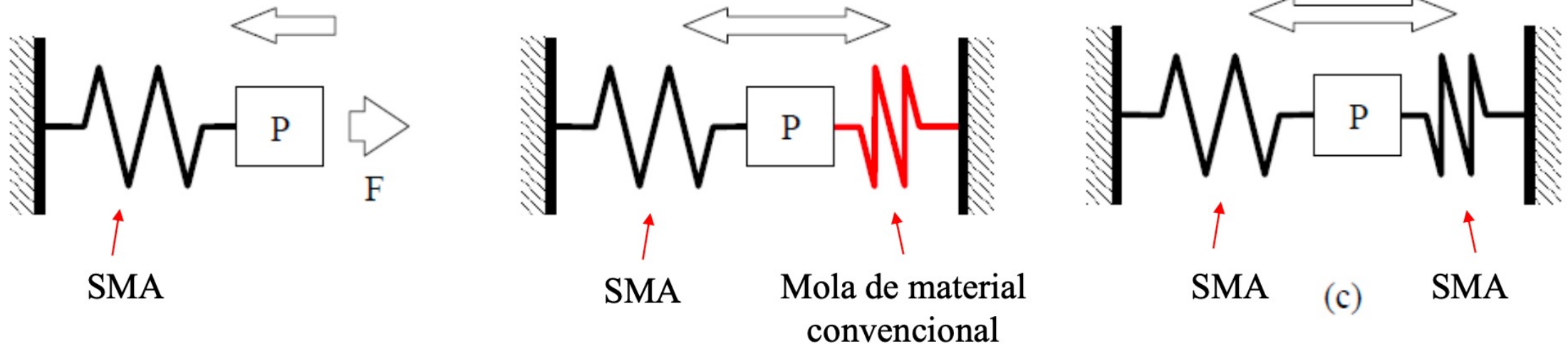
Plasticidade Induzida por Transformação de Fase (TRIP)



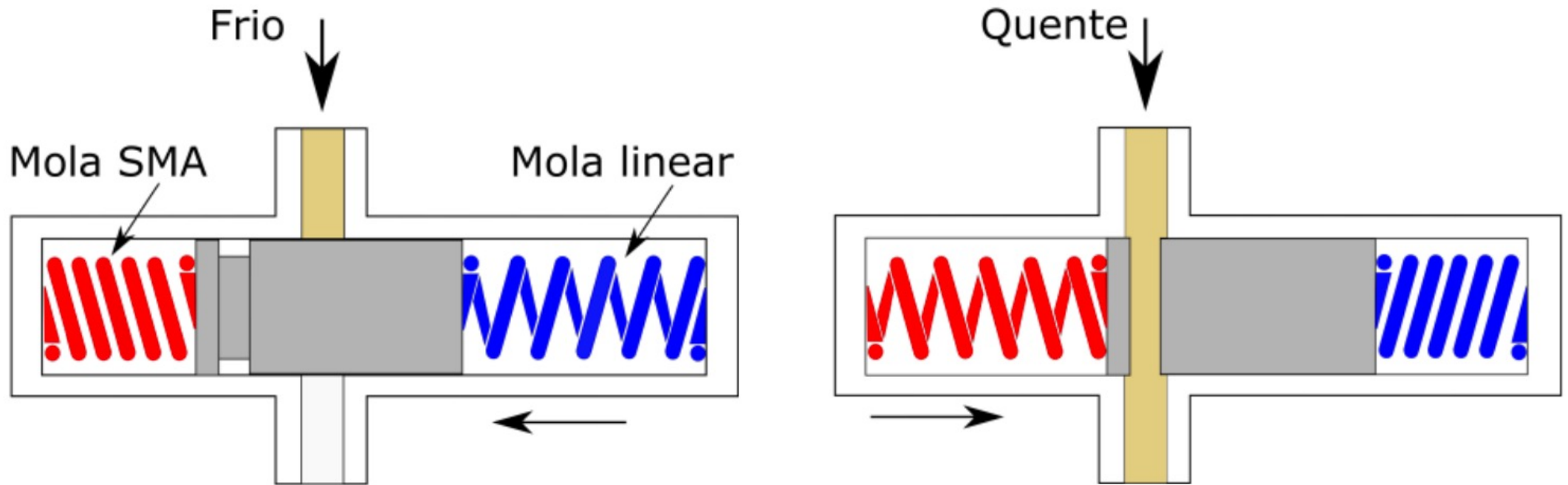
Dornelas (2020)

- Aparecimento de deformação residual ao longo de ciclos de carregamento
- Causas: Surgimento de tensões internas associadas à mudança de volume (ou forma).
- Há plastificação mesmo sem atingir superfície de escoamento

Tipos Básicos de Atuadores com Memória de Forma

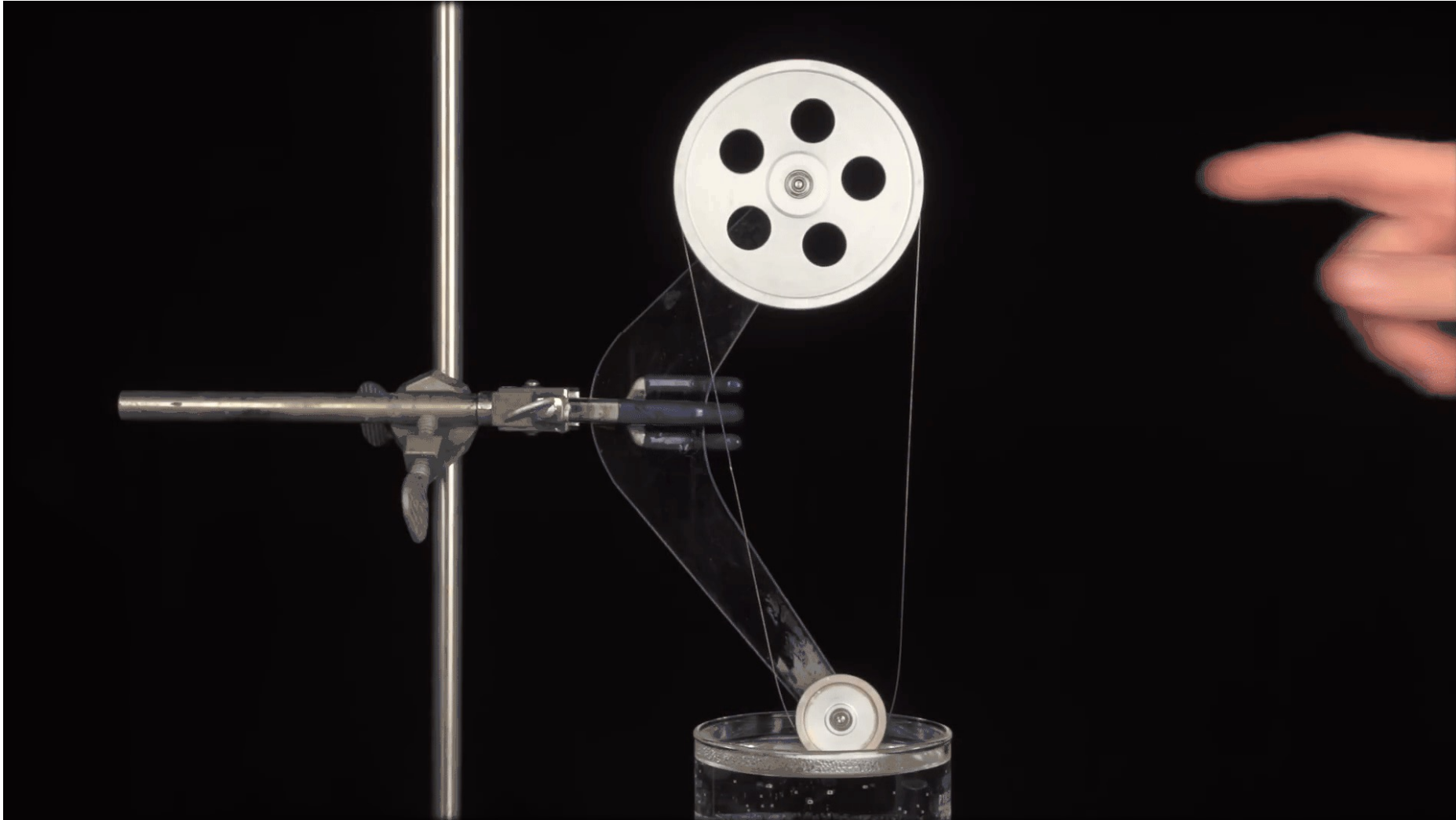


Tipos Básicos de Atuadores com Memória de Forma



Dornelas (2020) | Stoeckel (1990)

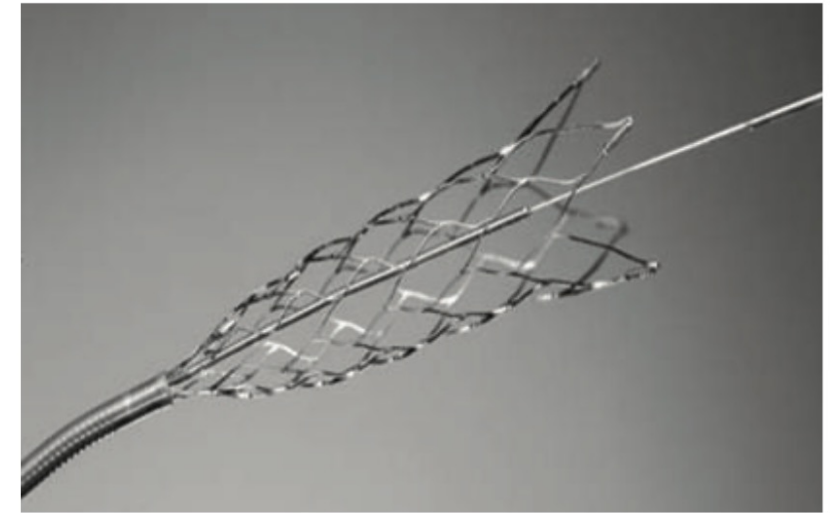
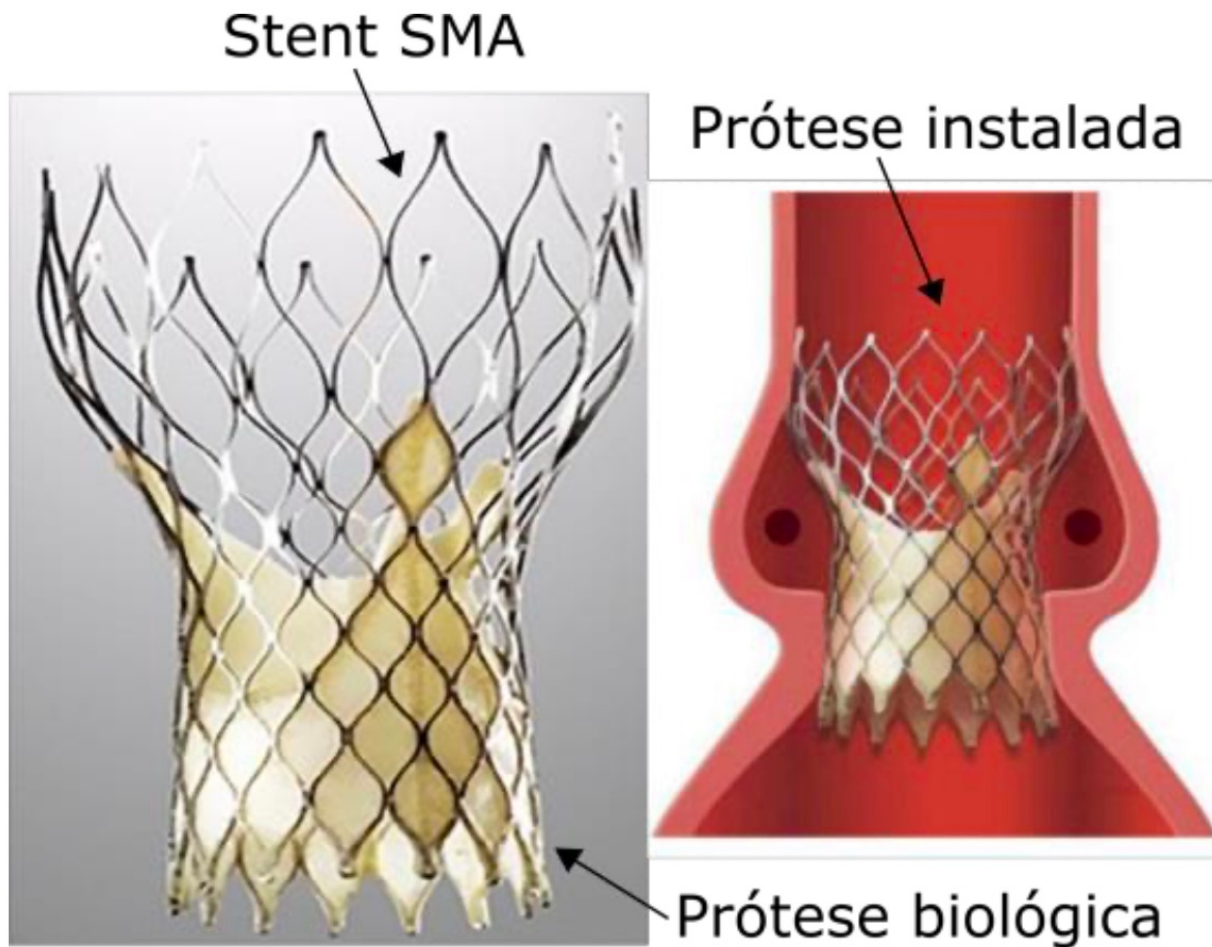
Motor de Nitinol



Rotorbearing system with SMAs

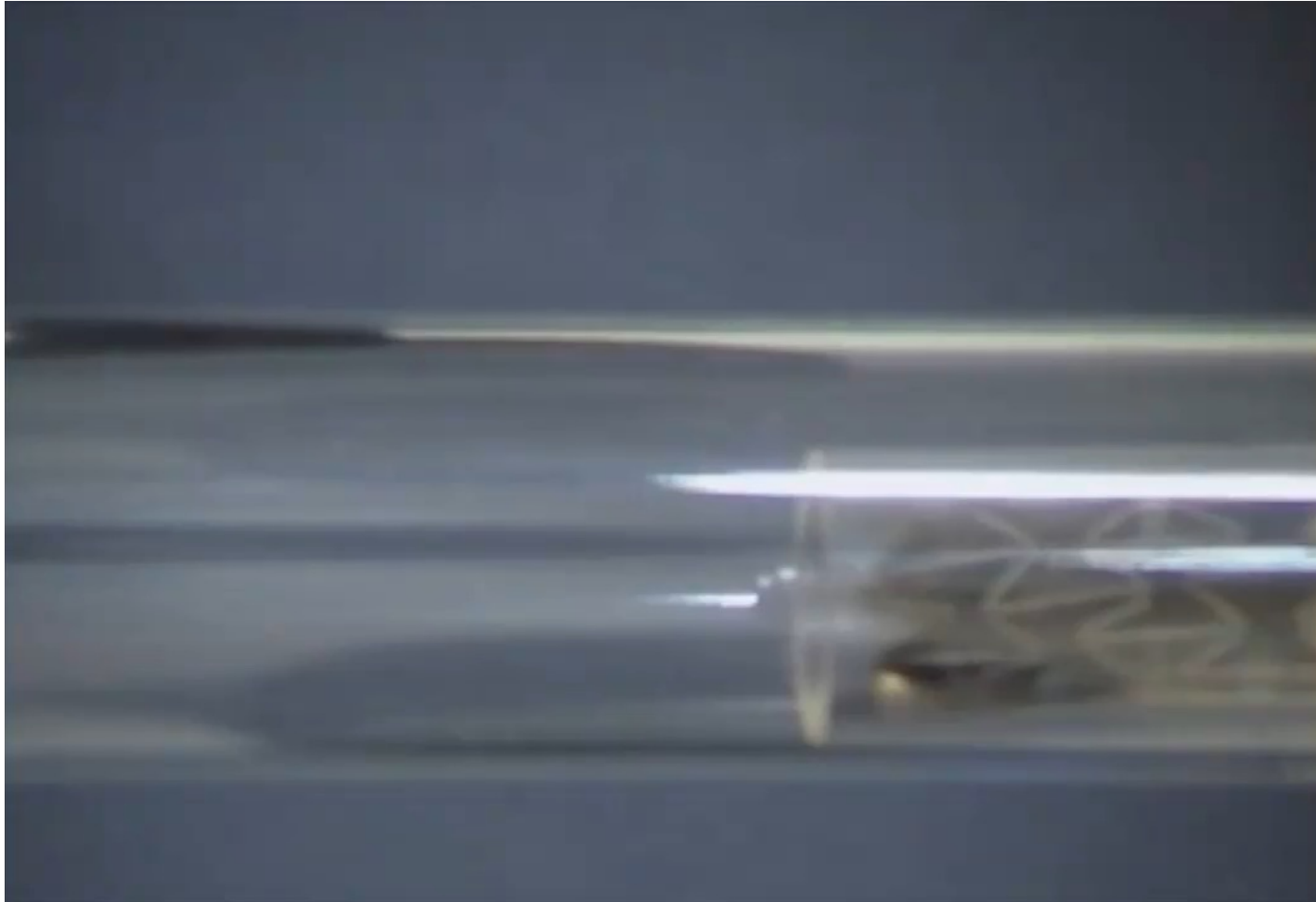
Temperature dependent behaviour

Aplicações Biomédicas – Stents Pseudoelásticos



Petrini & Migliavacca (2011)

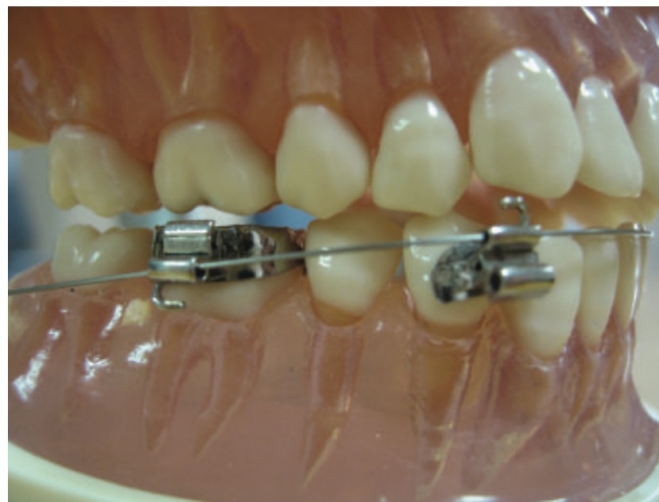
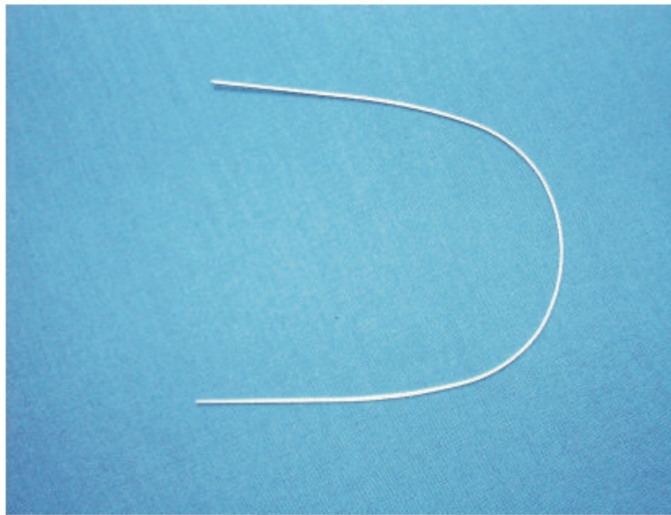
Aplicações Biomédicas – Stents Pseudoelásticos



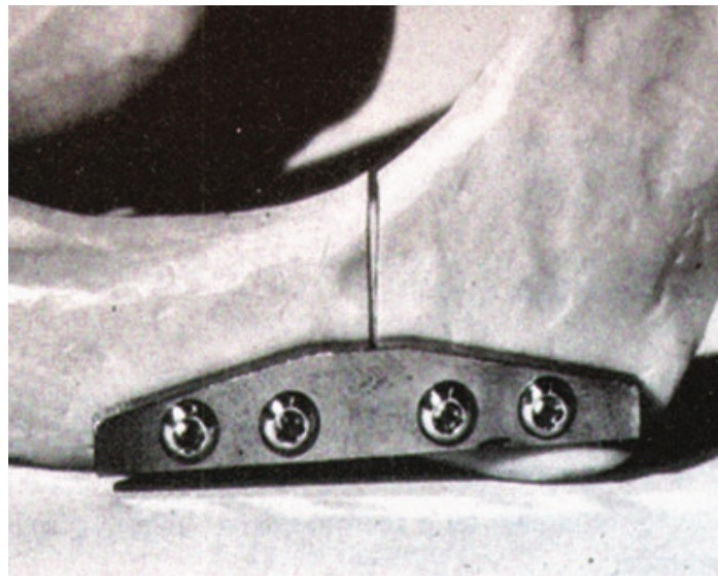
Kuribayashi et al (2006)



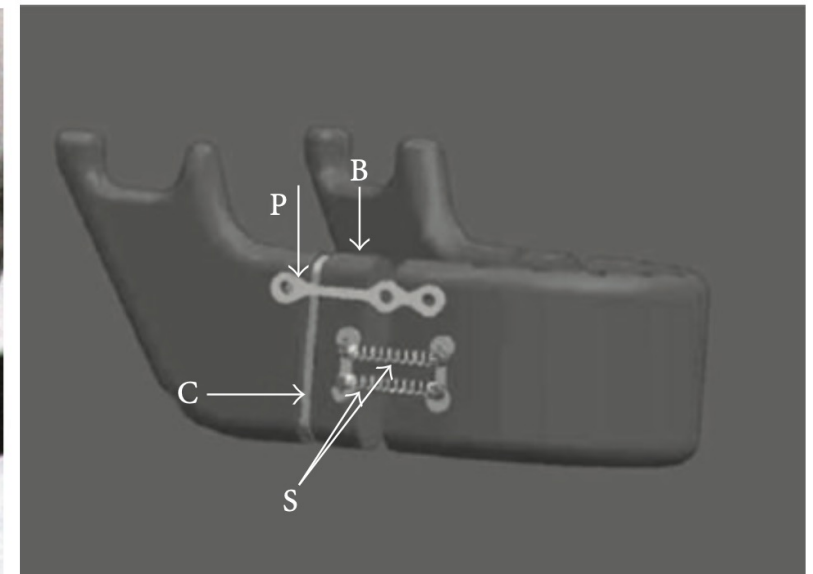
Aplicações Biomédicas – Próteses e Contenções



Petrini & Migliavacca (2011)

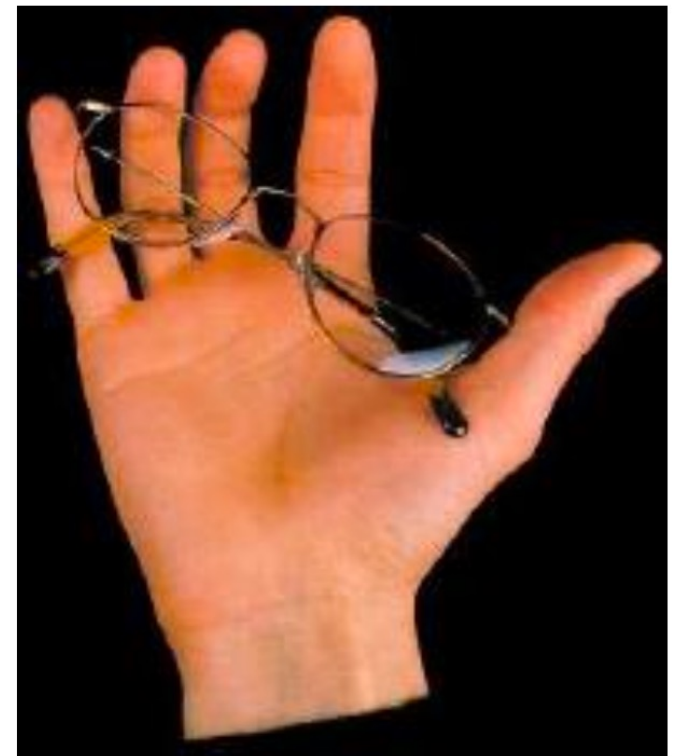


Duering et al. (1990)



Idelsohn et al. (2004)

Acessórios

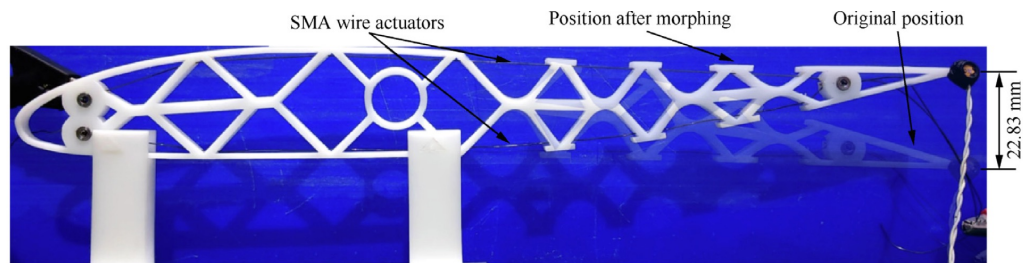


Aplicações Aeroespaciais

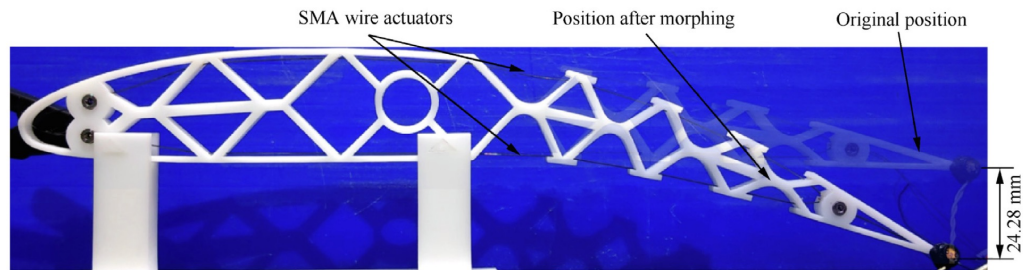


Hartl & Lagoudas (2007)

Aplicações Aeroespaciais

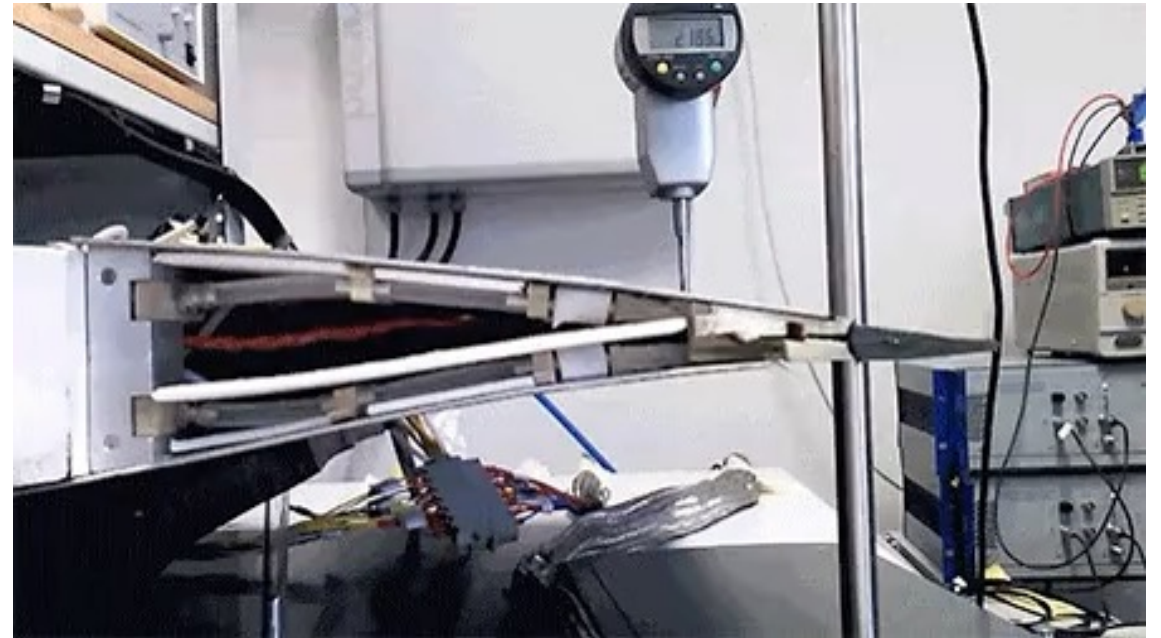


(a) Upward morphing effect



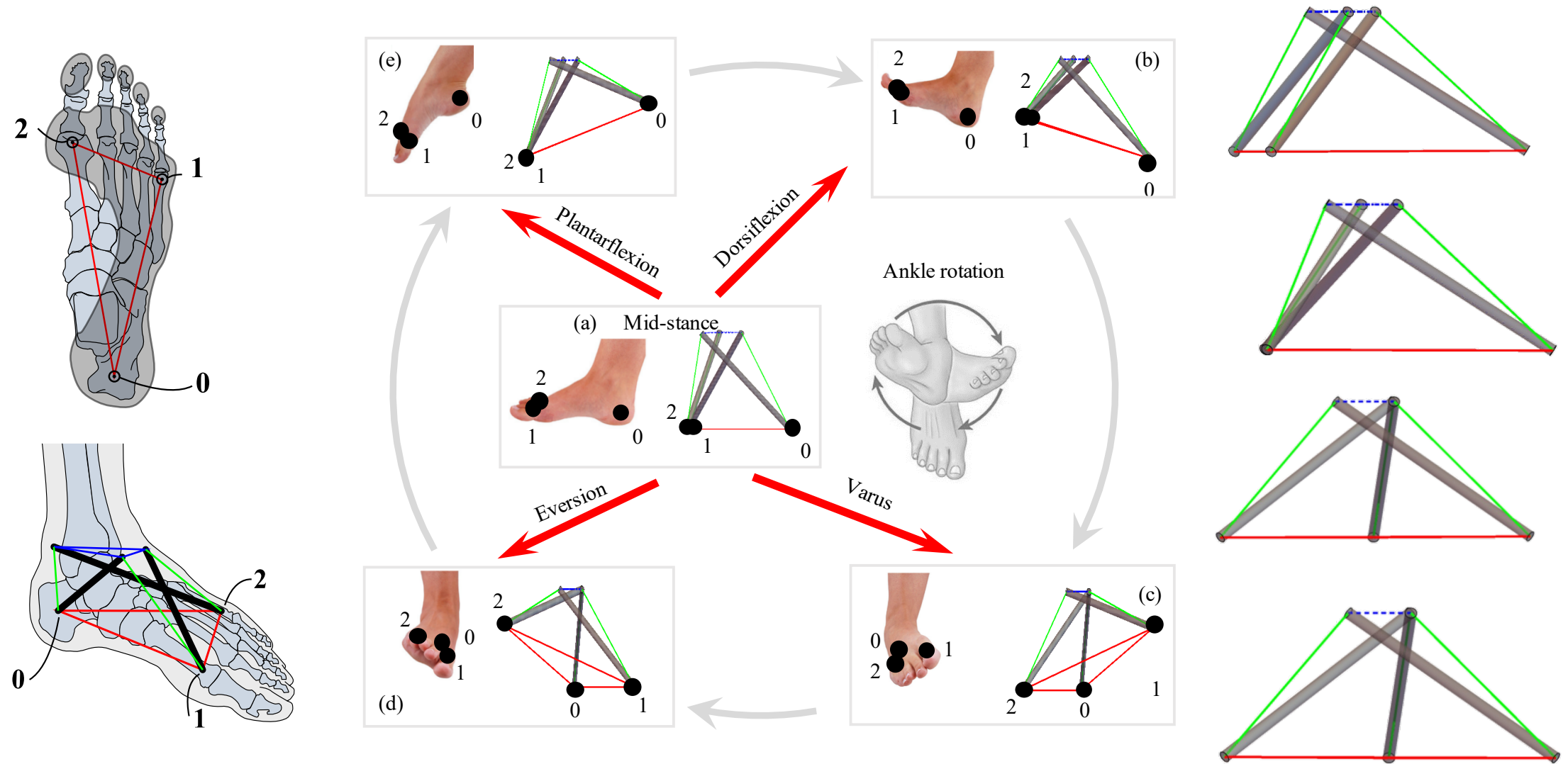
(b) Downward morphing effect

Yang et al (2024)



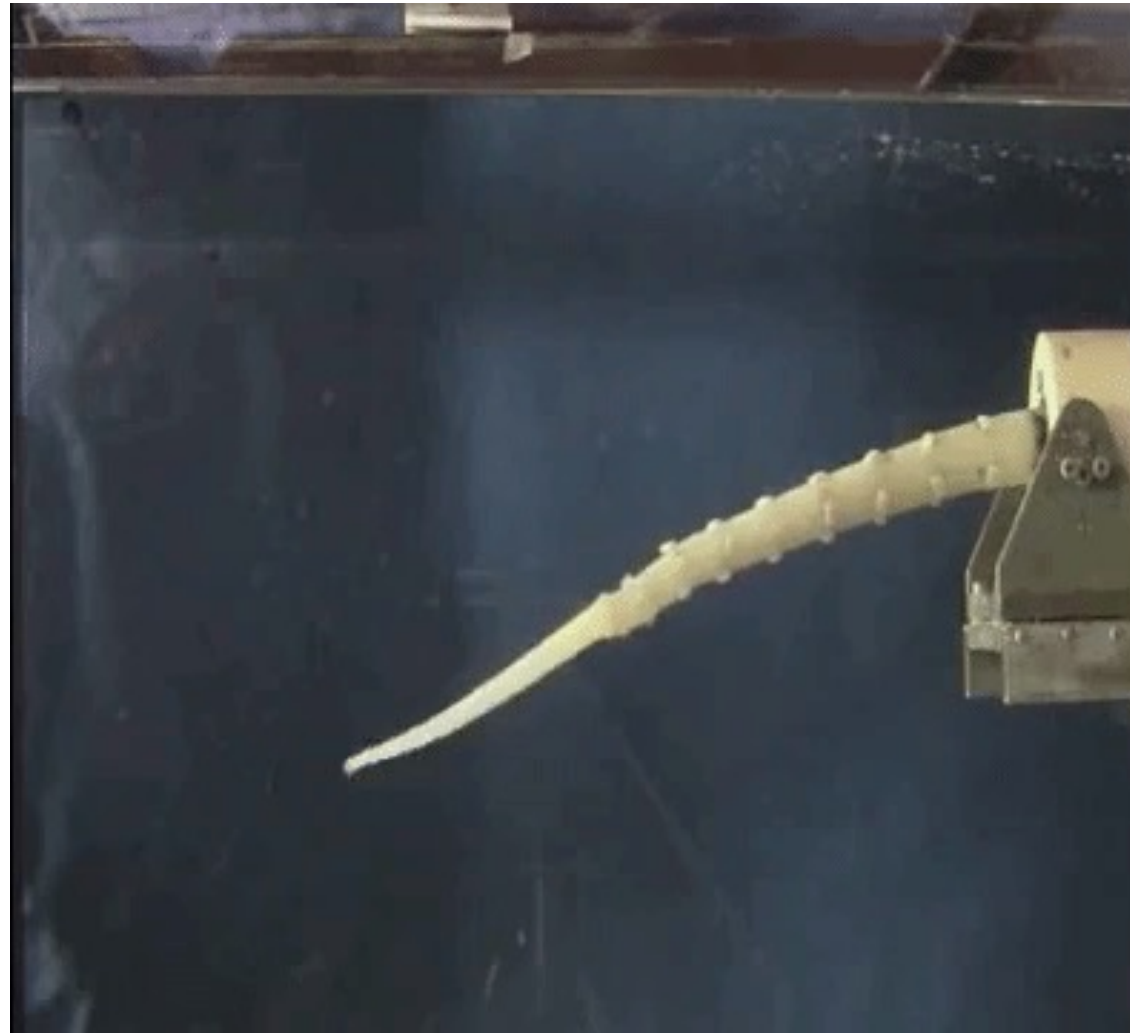
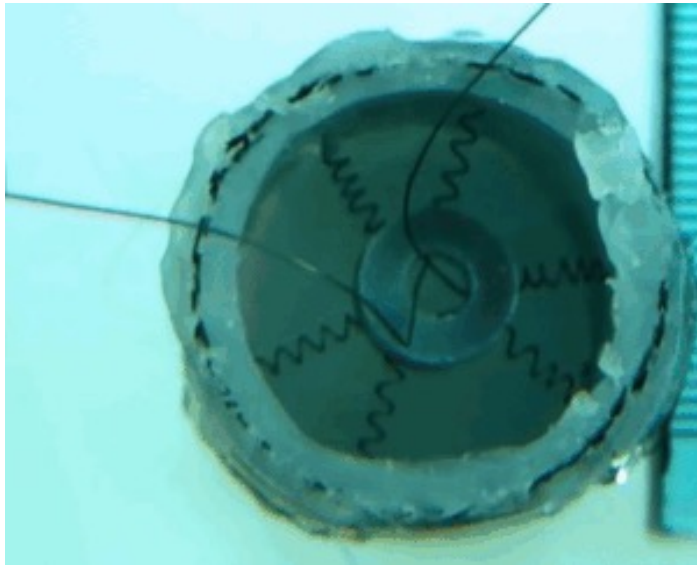
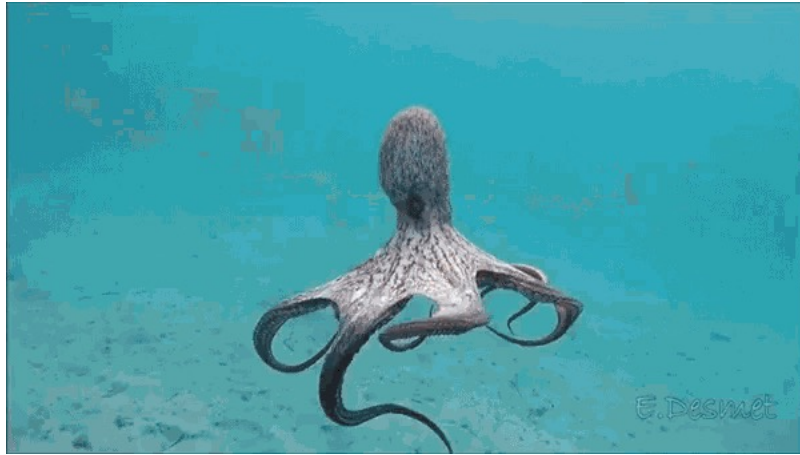
Carvalho et al (2022)

Biotensengridade com Memória



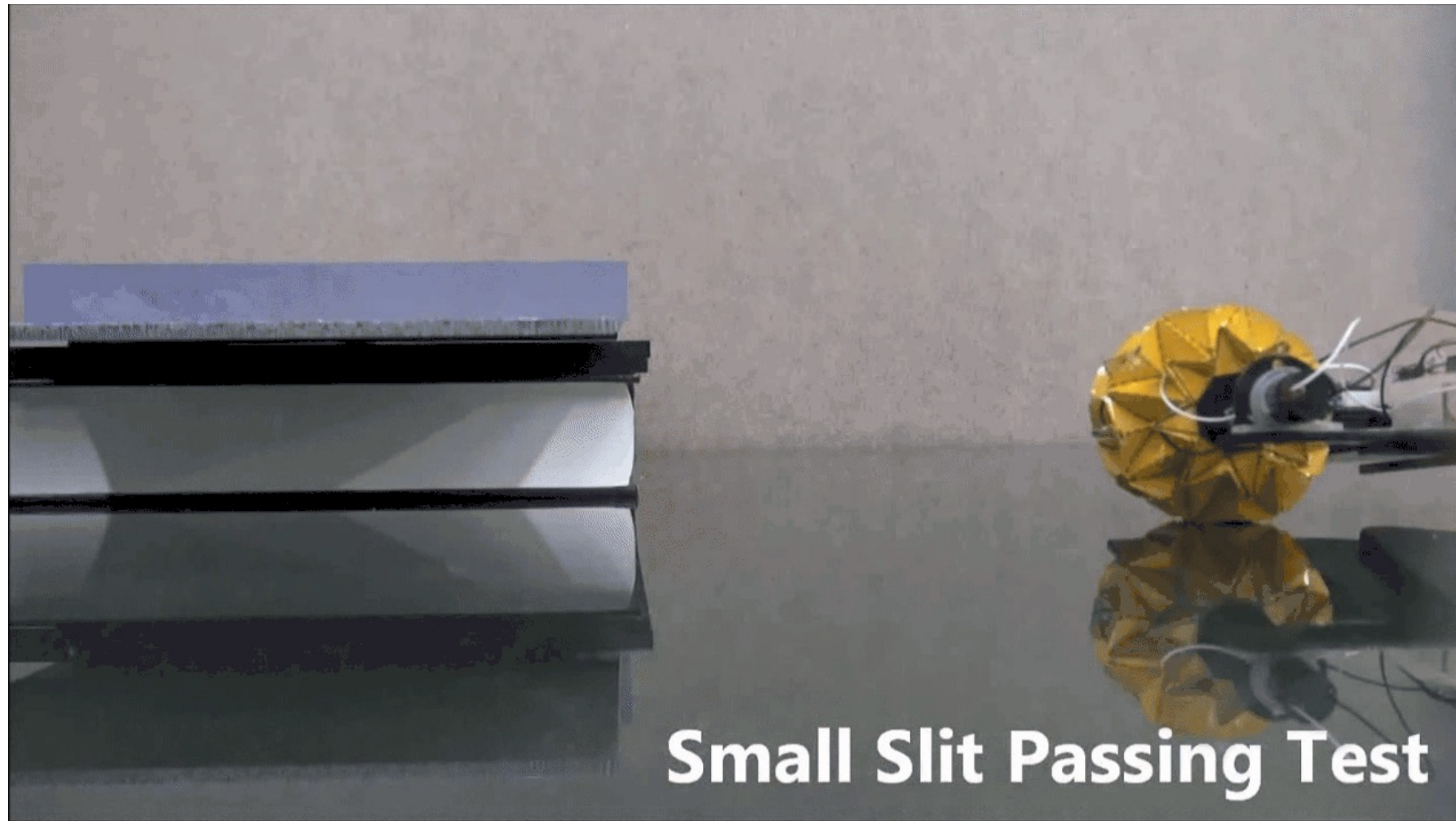
Brandão & Savi (2022)

Músculos Artificiais (Atuadores)



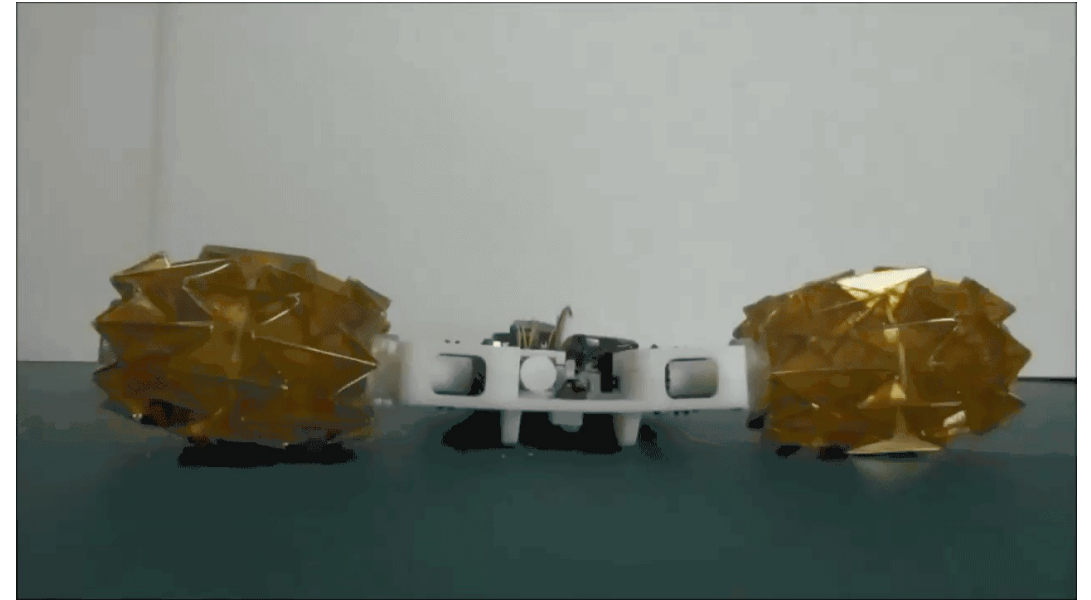
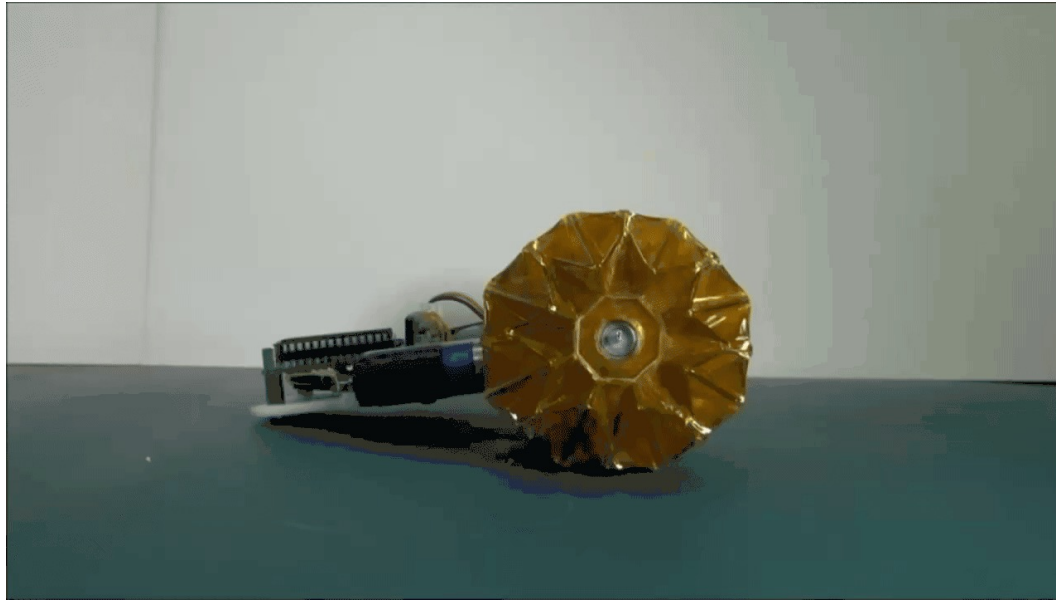
Cianchetti et al. (2014)

Estruturas Adaptativas – Roda Origami com Memória

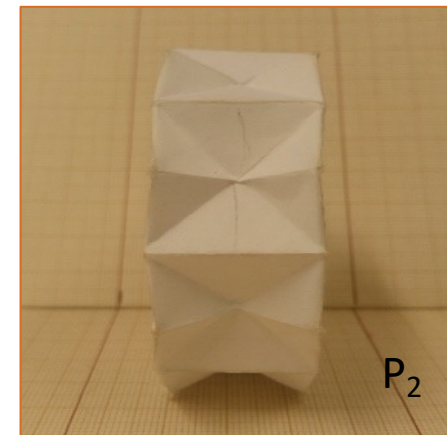
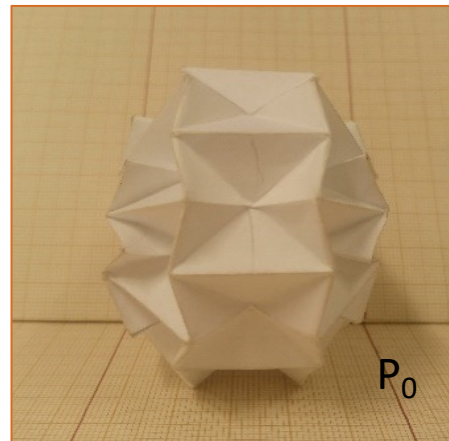
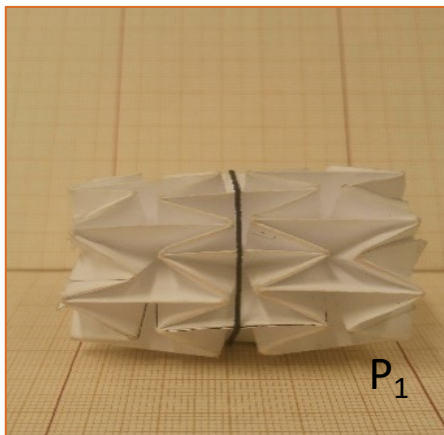


Lee et al. (2013)

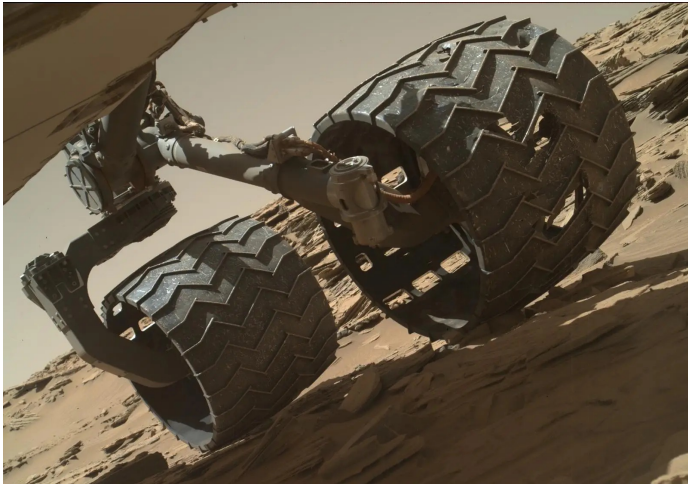
Estruturas Adaptativas – Roda Origami com Memória



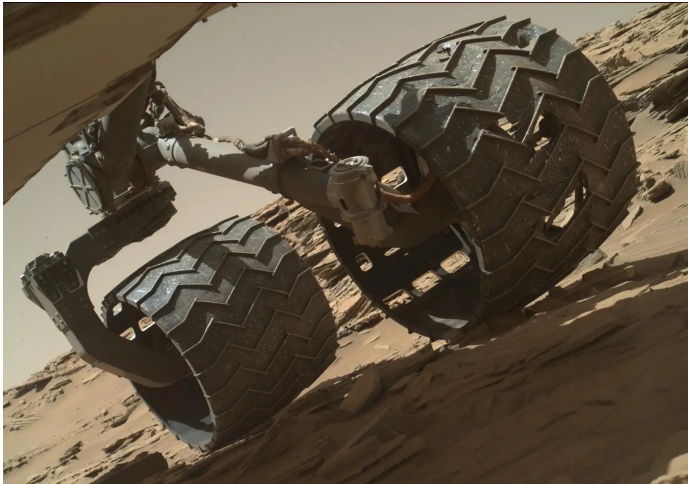
Lee et al. (2013)



Estruturas Adaptativas – Roda Pseudoelástica do Mars Rover



Estruturas Adaptativas – Roda Pseudoelástica do Mars Rover



Estruturas Adaptativas – Bicicletas



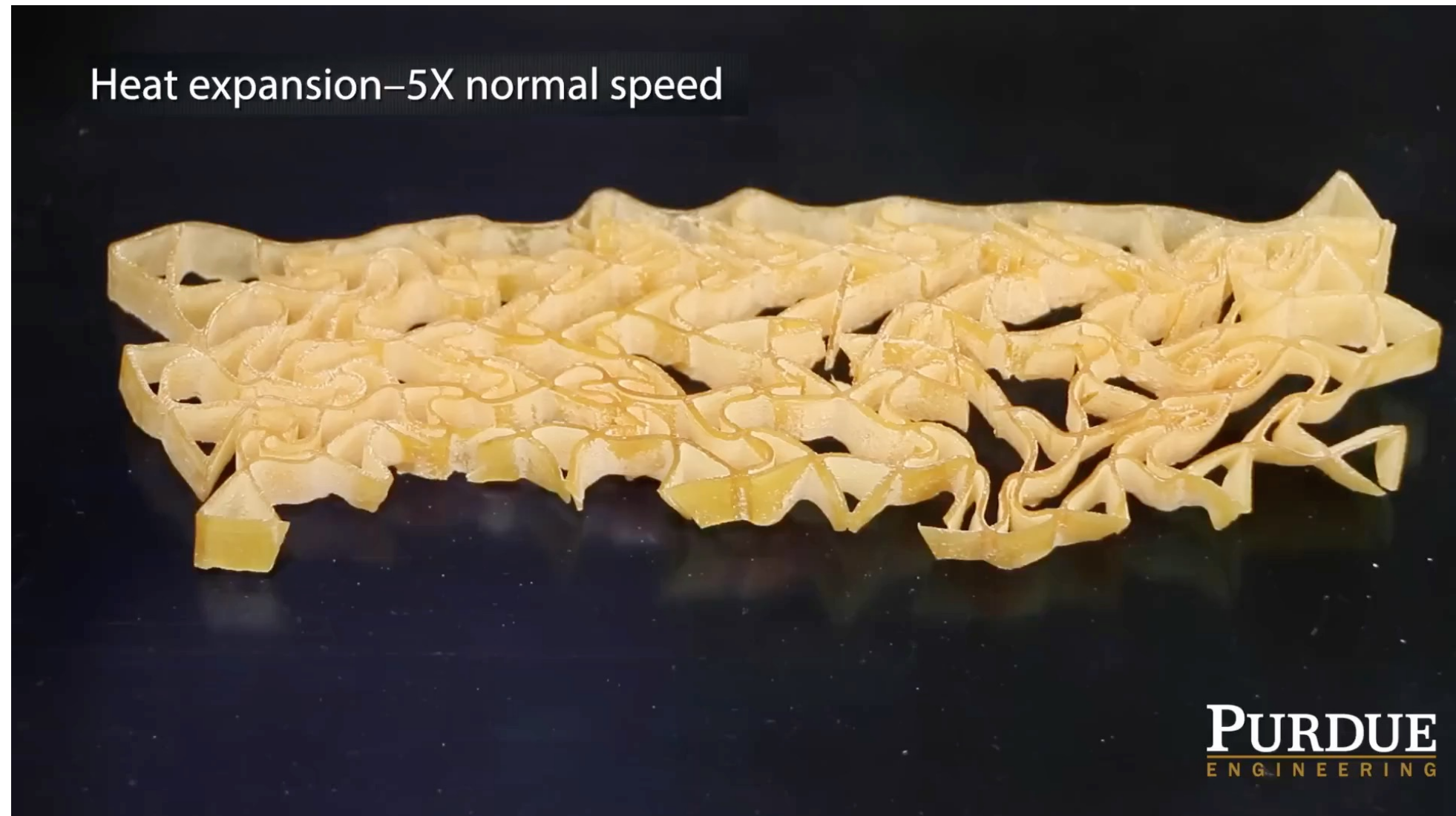
The Smart Tire Company (2025)

Polímeros com Memória de Forma (SMPs)

Efeito Memória de Forma

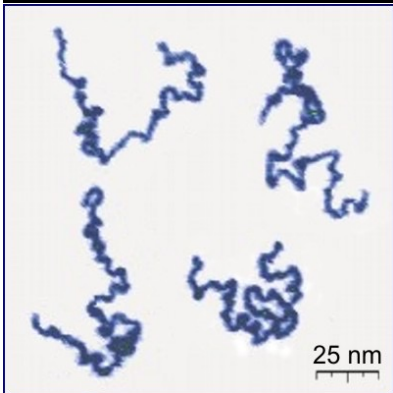
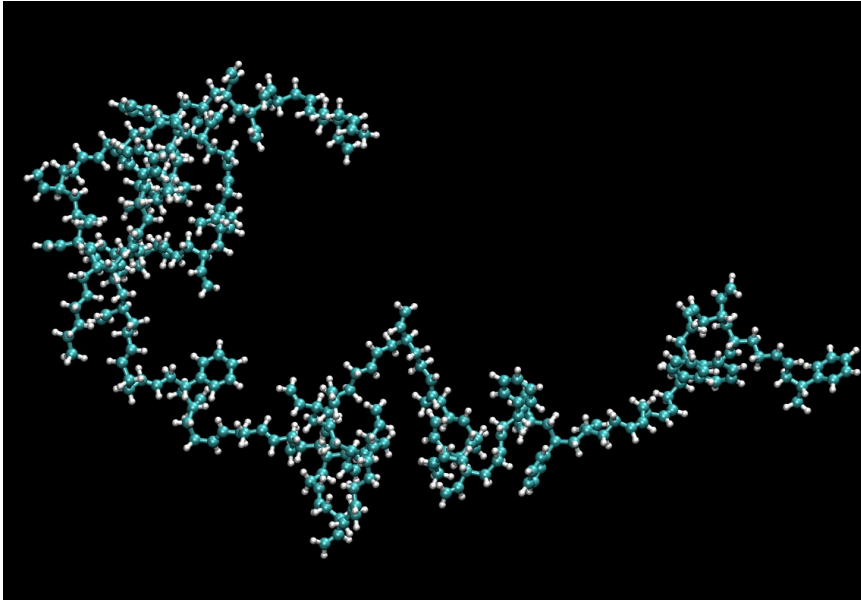


Efeito Memória de Forma

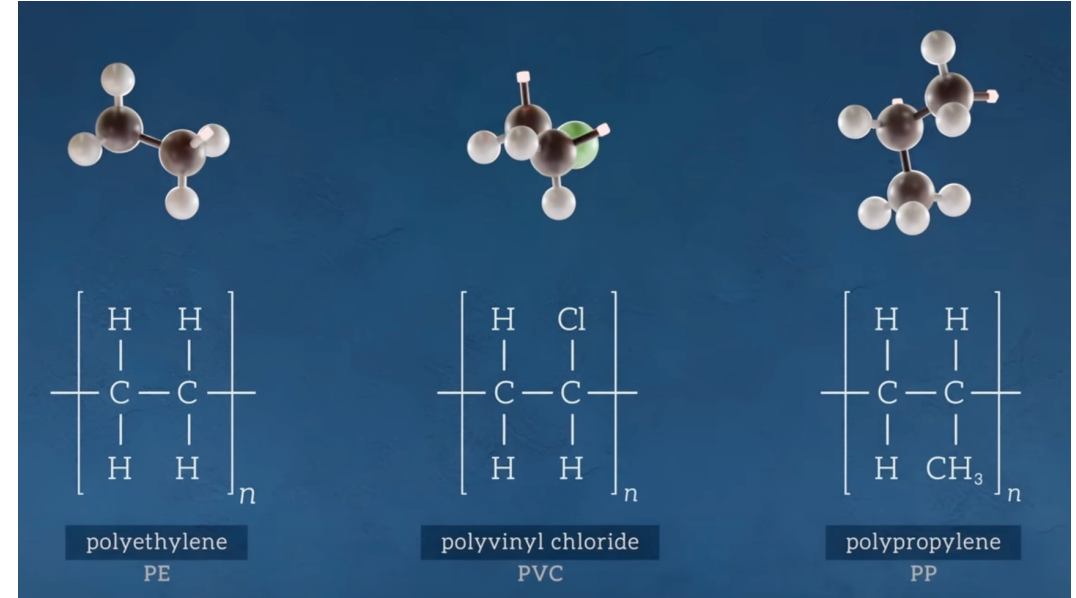


Estrutura de um Polímero

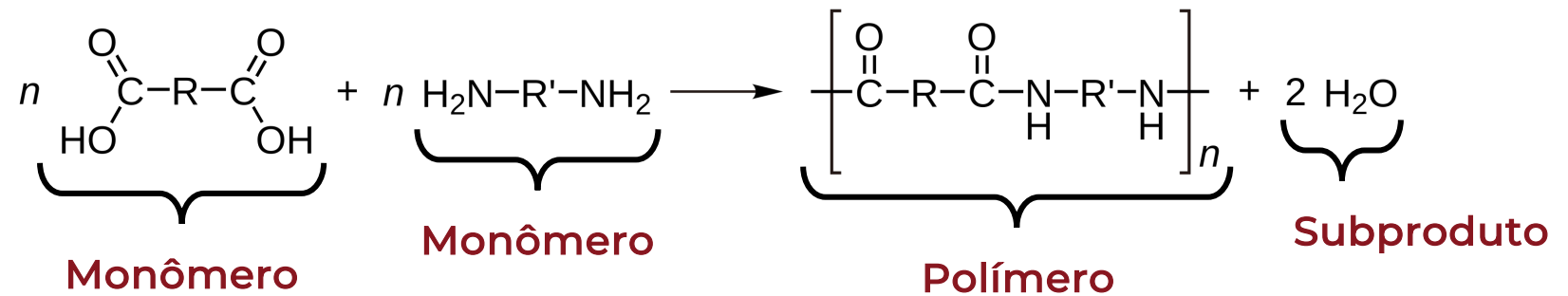
Cadeias Poliméricas



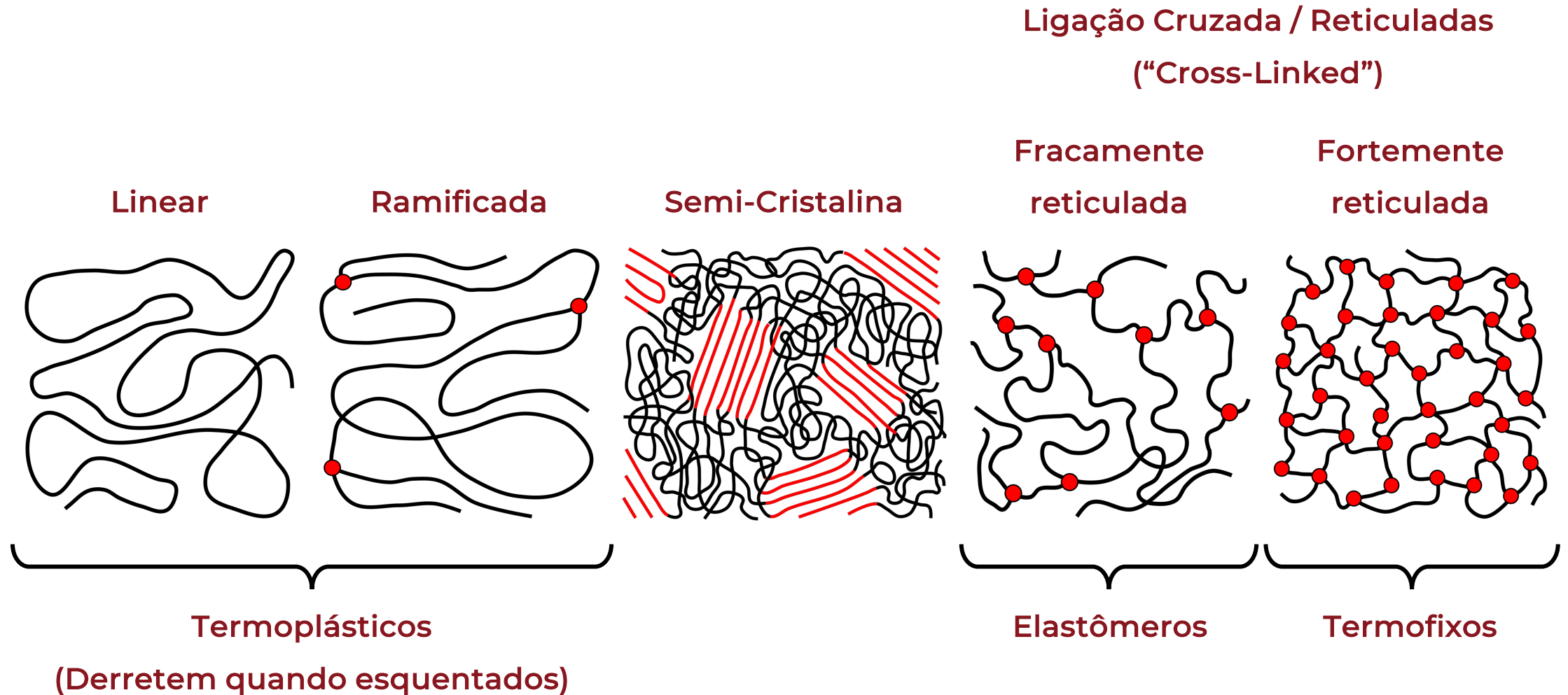
Estrutura Química (Mero)



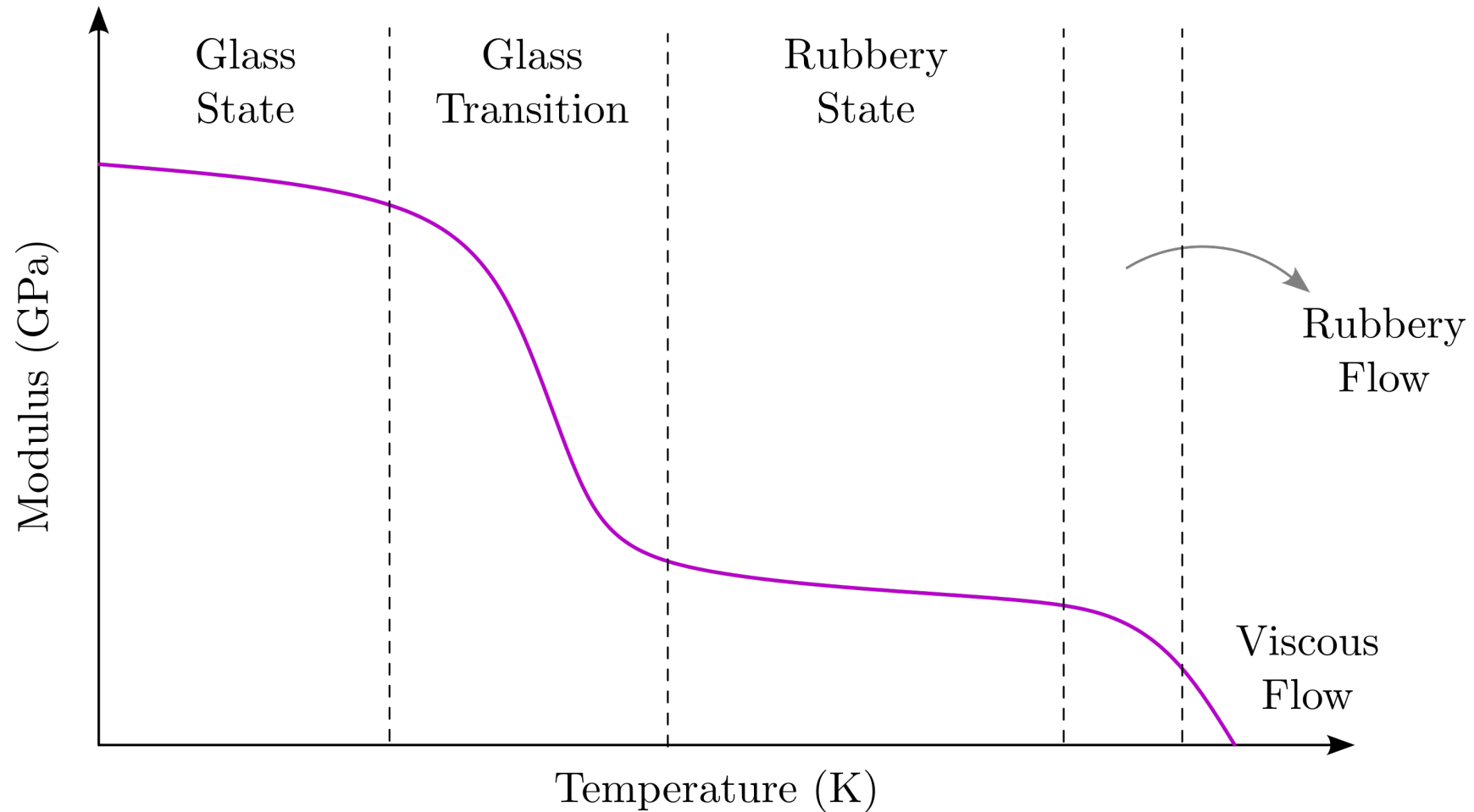
Polimerização



Estrutura de um Polímero



Variação de Propriedades com a Temperatura

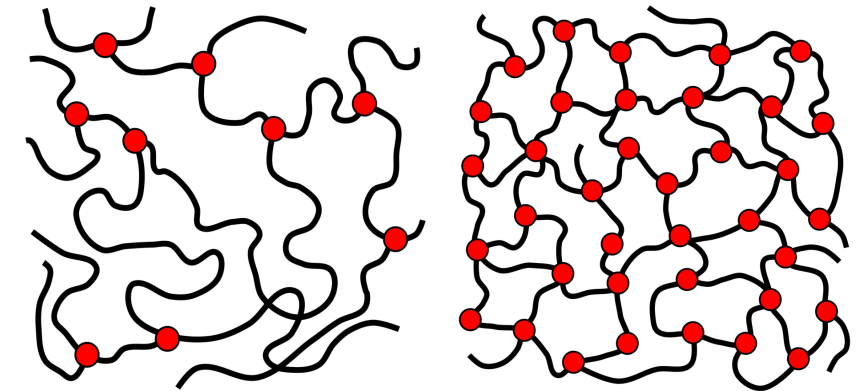


Shape Memory Polymers

Ligação Cruzada / Reticuladas
("Cross-Linked")

Fracamente
reticulada

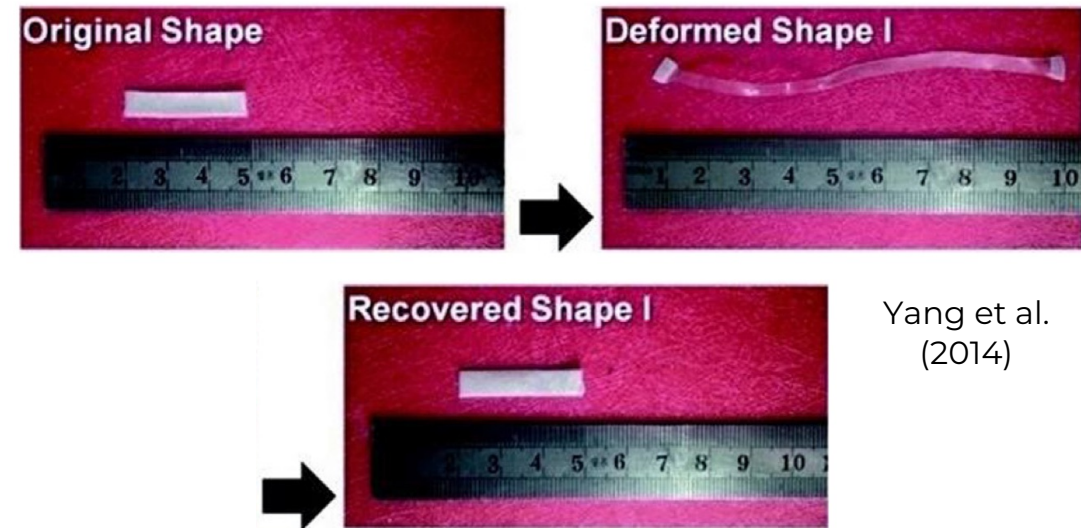
Fortemente
reticulada



Elastômeros

Termofixos

- Mais leves
- Capacidade de maiores deformações
- Possibilidade de mais de uma "memória" (estado programado)
- Facilmente manufaturados e mais baratos



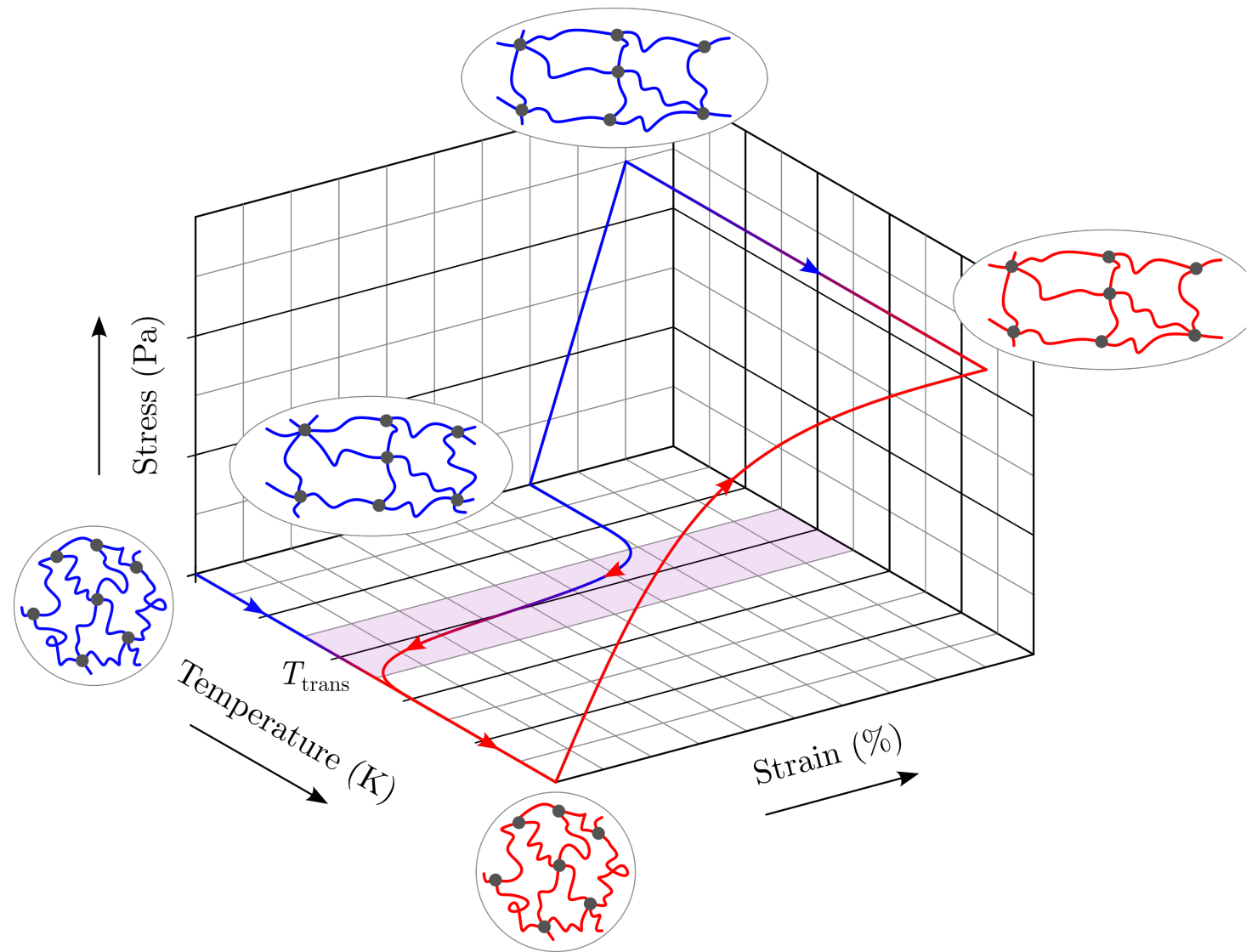
Yang et al.
(2014)

Shape Memory Polymers



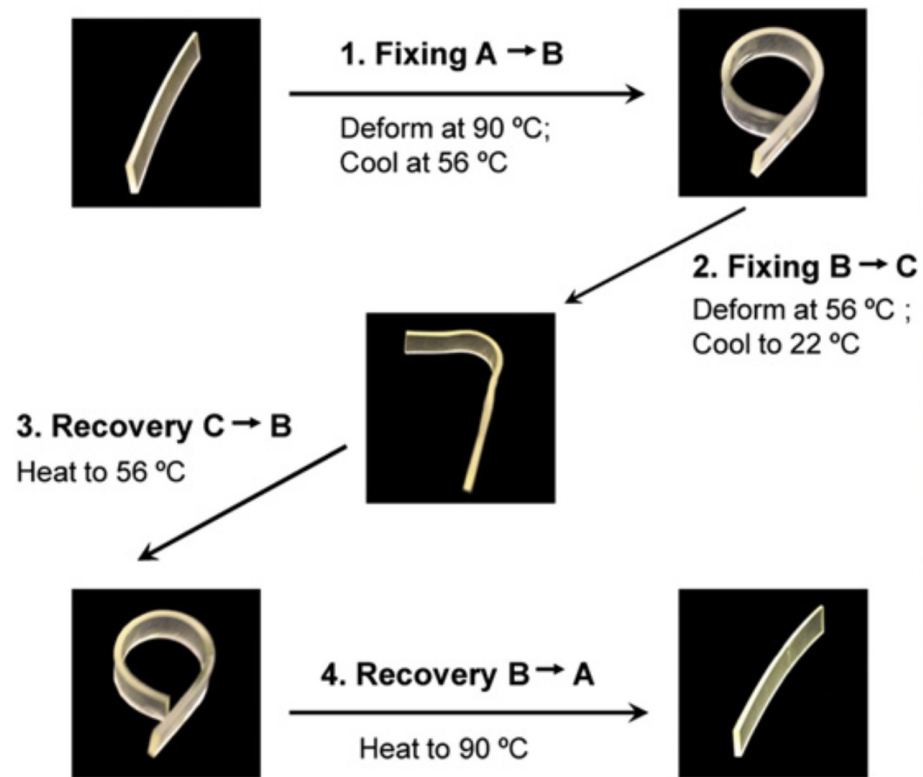
Yang et al. (2014)

Ciclo Termomecânico de Memória de Forma (One Way)



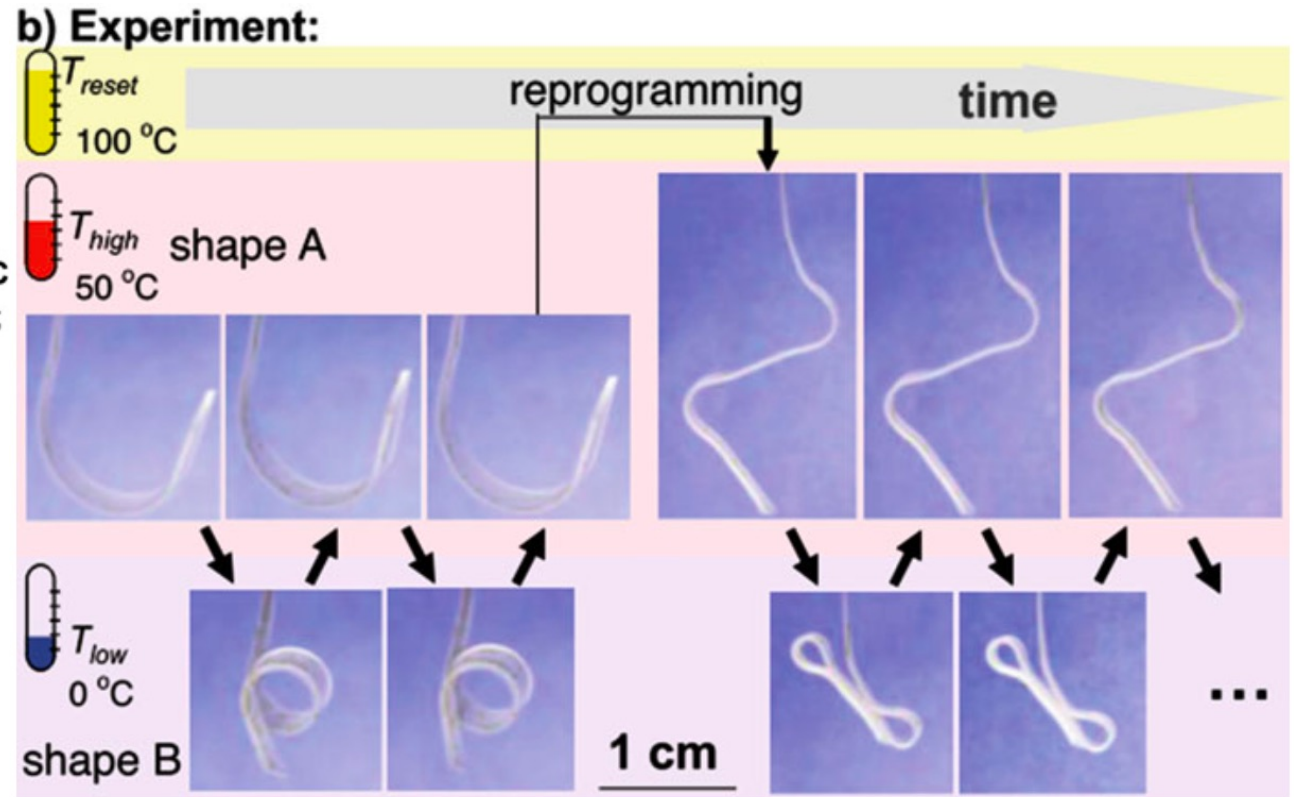
Outros Tipos

Triple/Multi-Shape



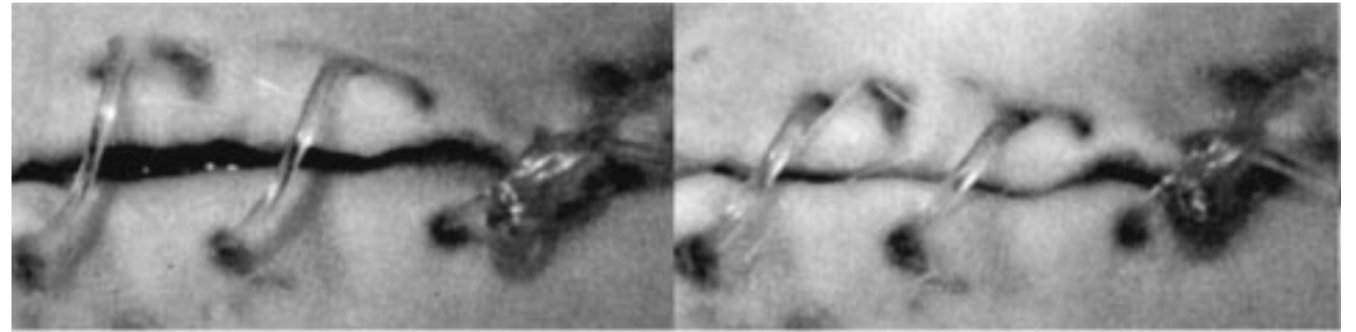
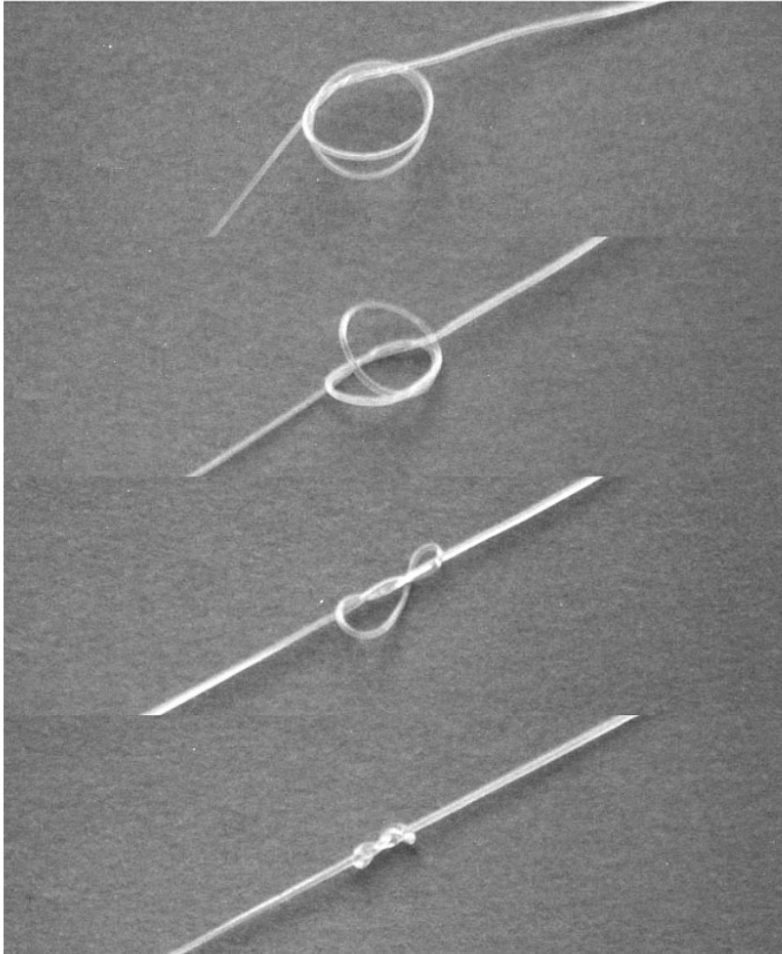
Xie et al. (2009)

Reversible Bidirectional SME (rbSME)



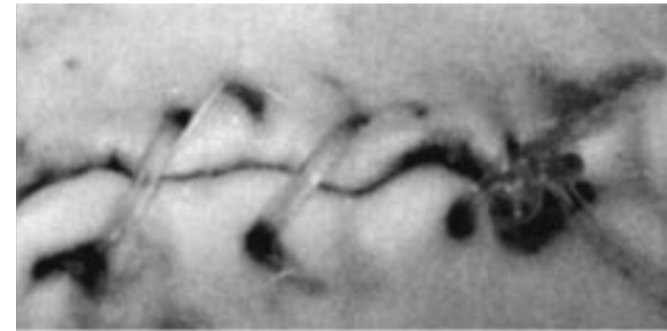
Behl et al. (2013)

Aplicações Biomédicas



20°C

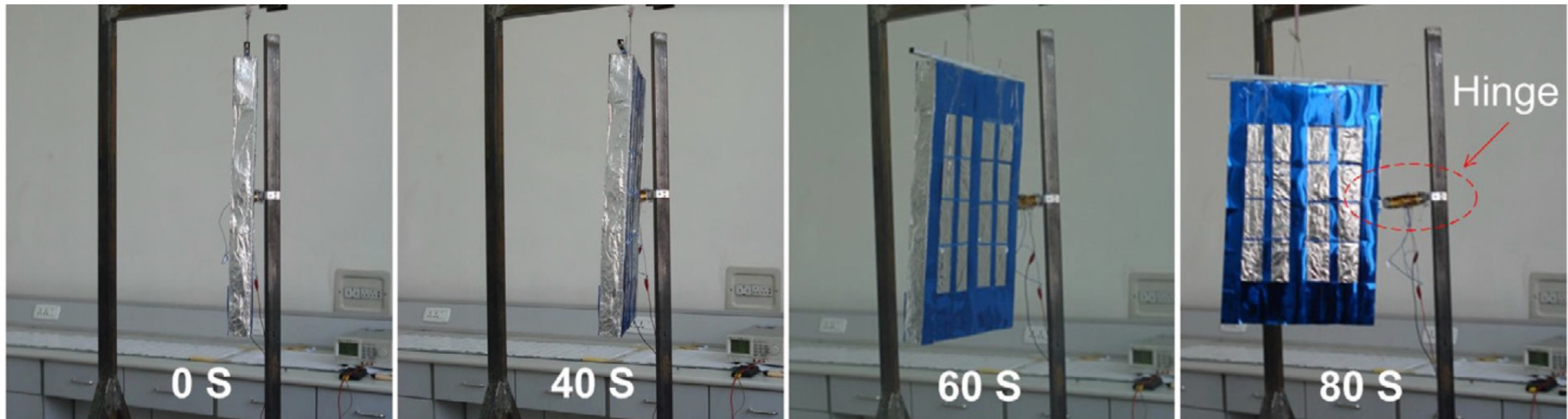
37°C



41°C

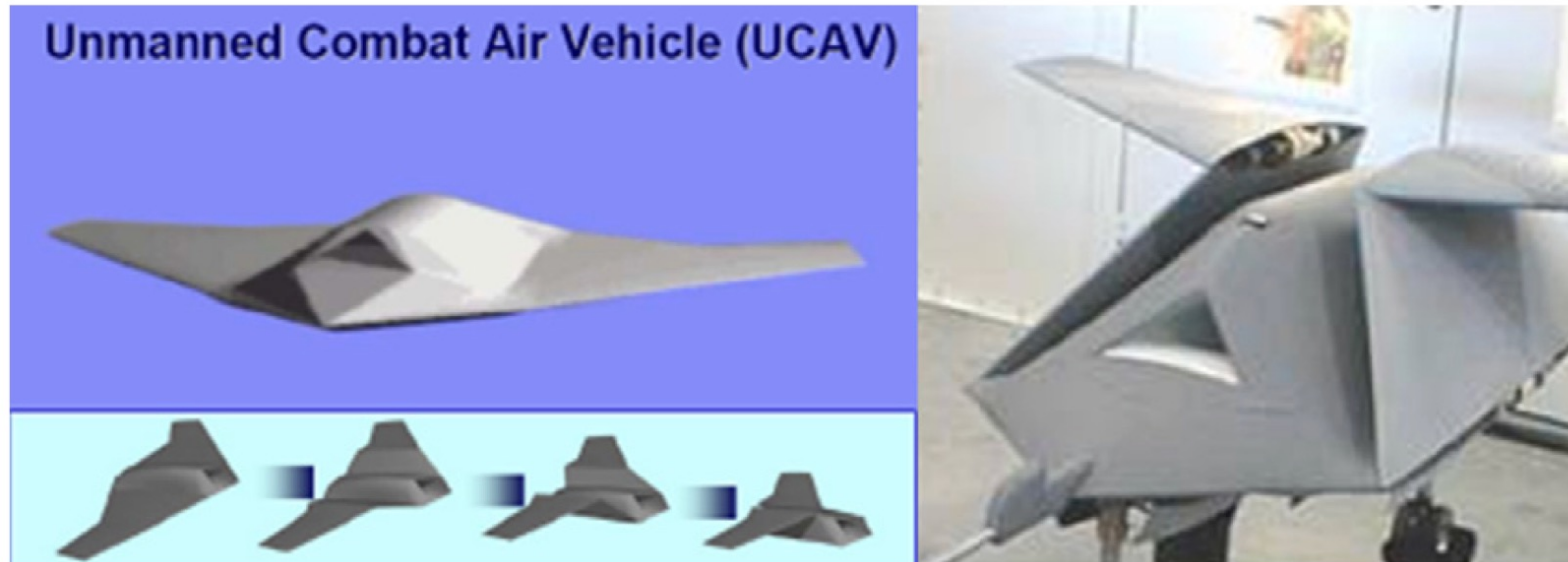
Lendlein & Langer (2002)

Aplicações Aeroespaciais



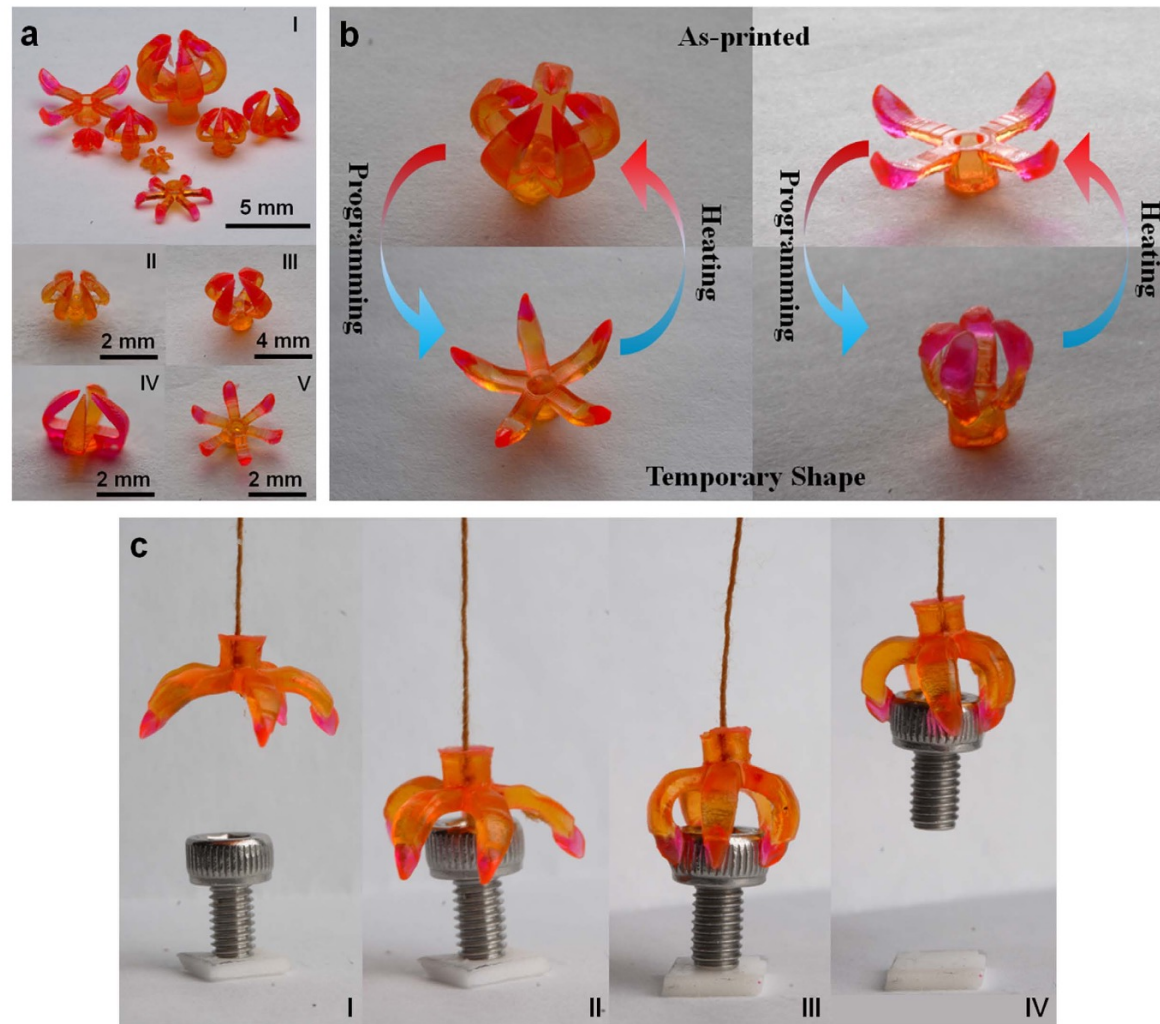
Lan et al. (2009)

Aplicações Aeroespaciais



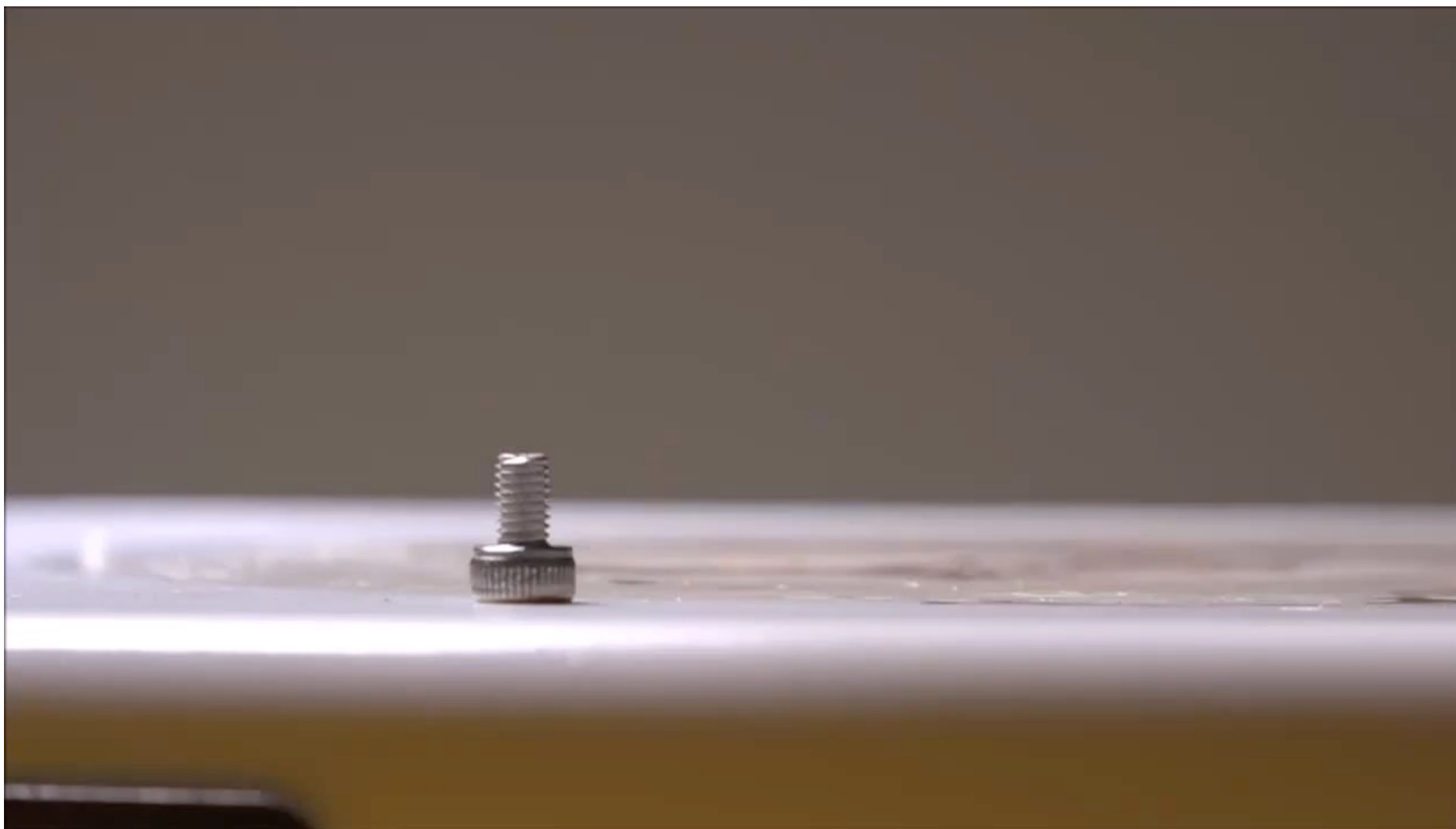
Bye & McClure. (2007)

Atuadores / Robótica



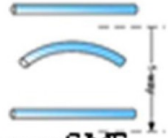
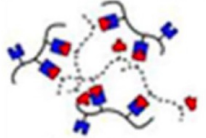
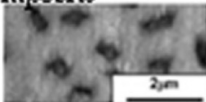
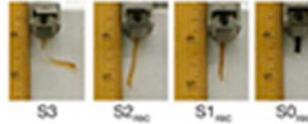
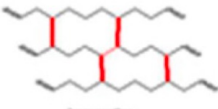
Ge et al. (2016)

Atuadores / Robótica



Ge et al. (2016)

Atuadores / Robótica

Composition & structure	Stimulus	Shape memory function
Block-copolymer 	Temperature 	One way SME 
Supramolecular polymer 	Electricity 	Two way SME 
	Magnetic 	
Polymer blend / composite 	Water sensitive 	Triple shape SME 
Polymer IPN/semi IPN 	Light/radiation 	Multi shape SME 
Crosslinked Homopolymer 	Oxidation-reduction 	Multi functionality 

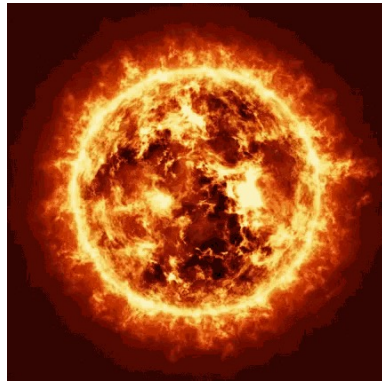
Ge et al. (2016)

Materiais Inteligentes: Acomplamento Multifísico

Mecânico



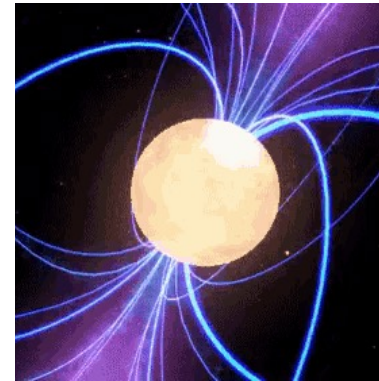
Térmico



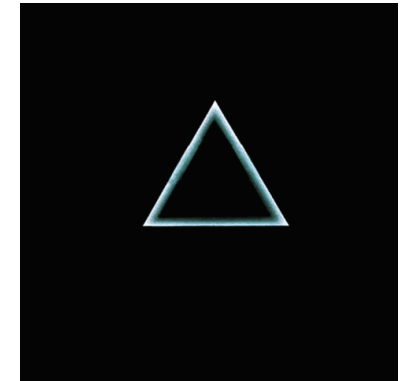
Elétrico



Magnético



Óptico

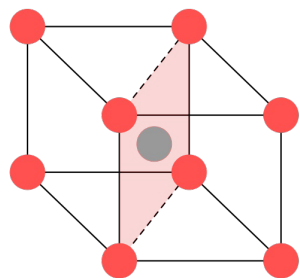


Magnetic Shape Memory Alloys (MSMAs)

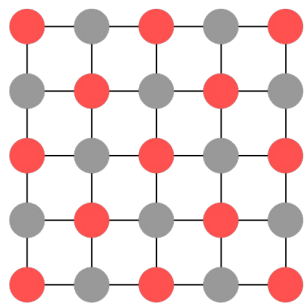
Deformação em Ligas com Memória de Forma

→ Mecanismo de transformação de fase tipo sólido-sólido

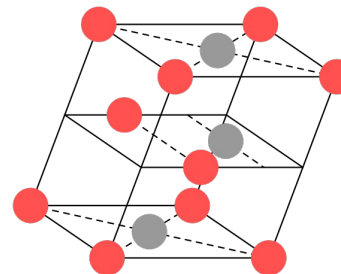
Austenita



Estável em alta temperatura

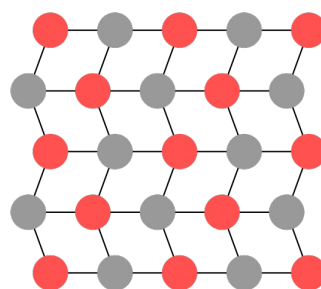


Martensita

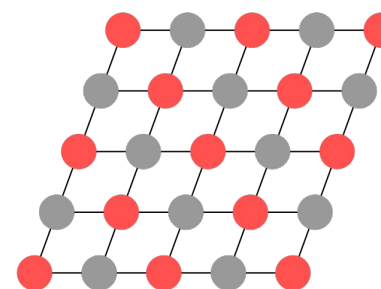


Estável em baixa temperatura

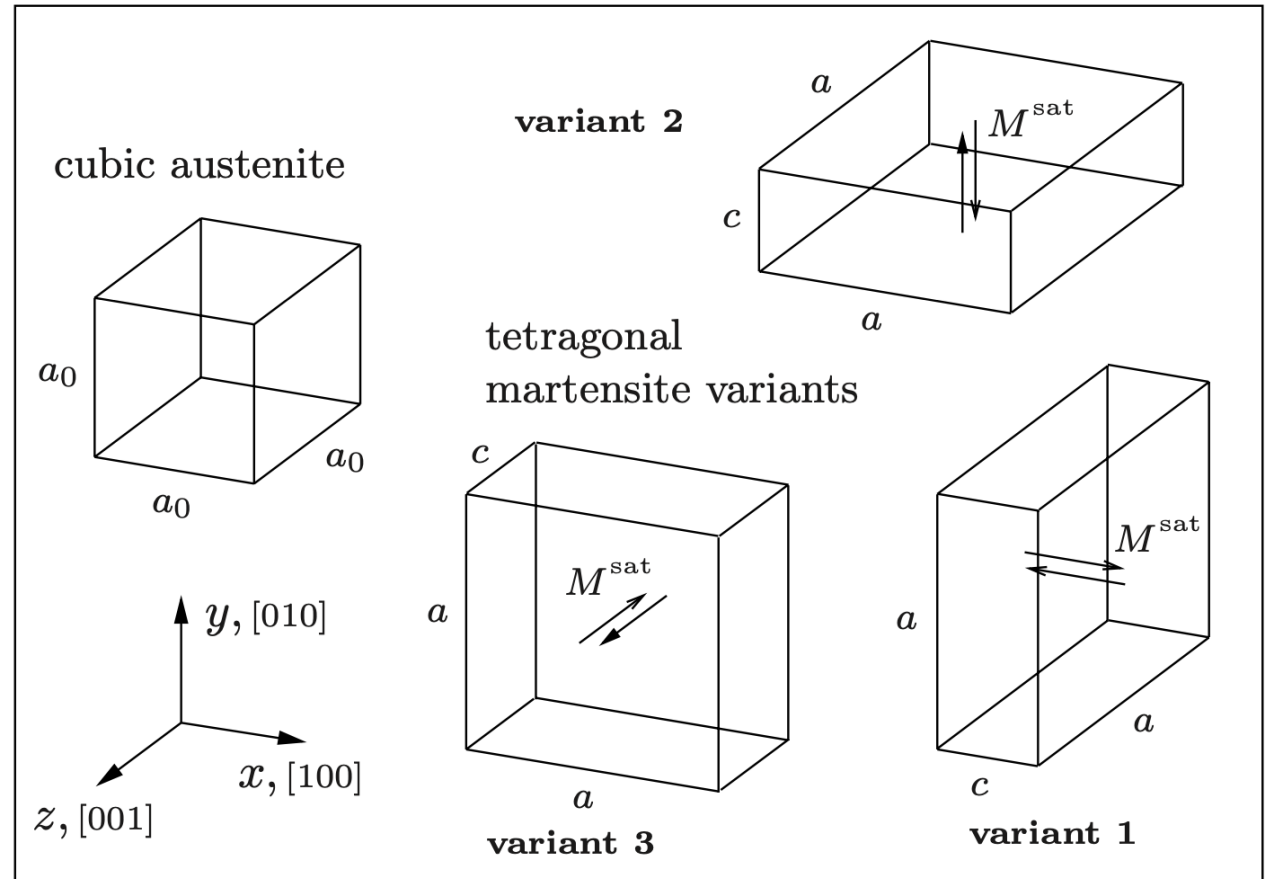
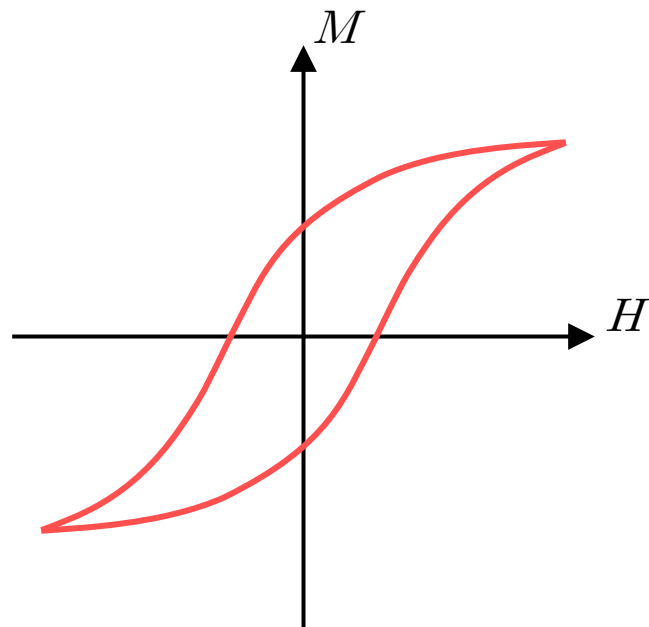
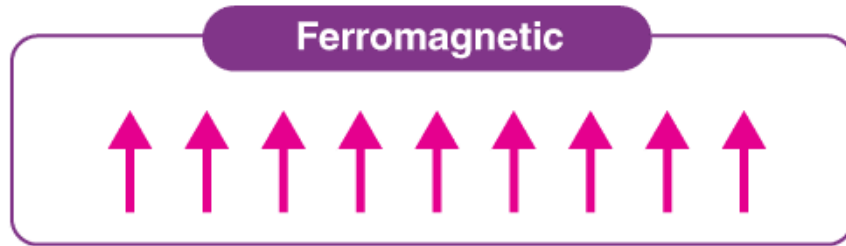
Maclada



Demaclada

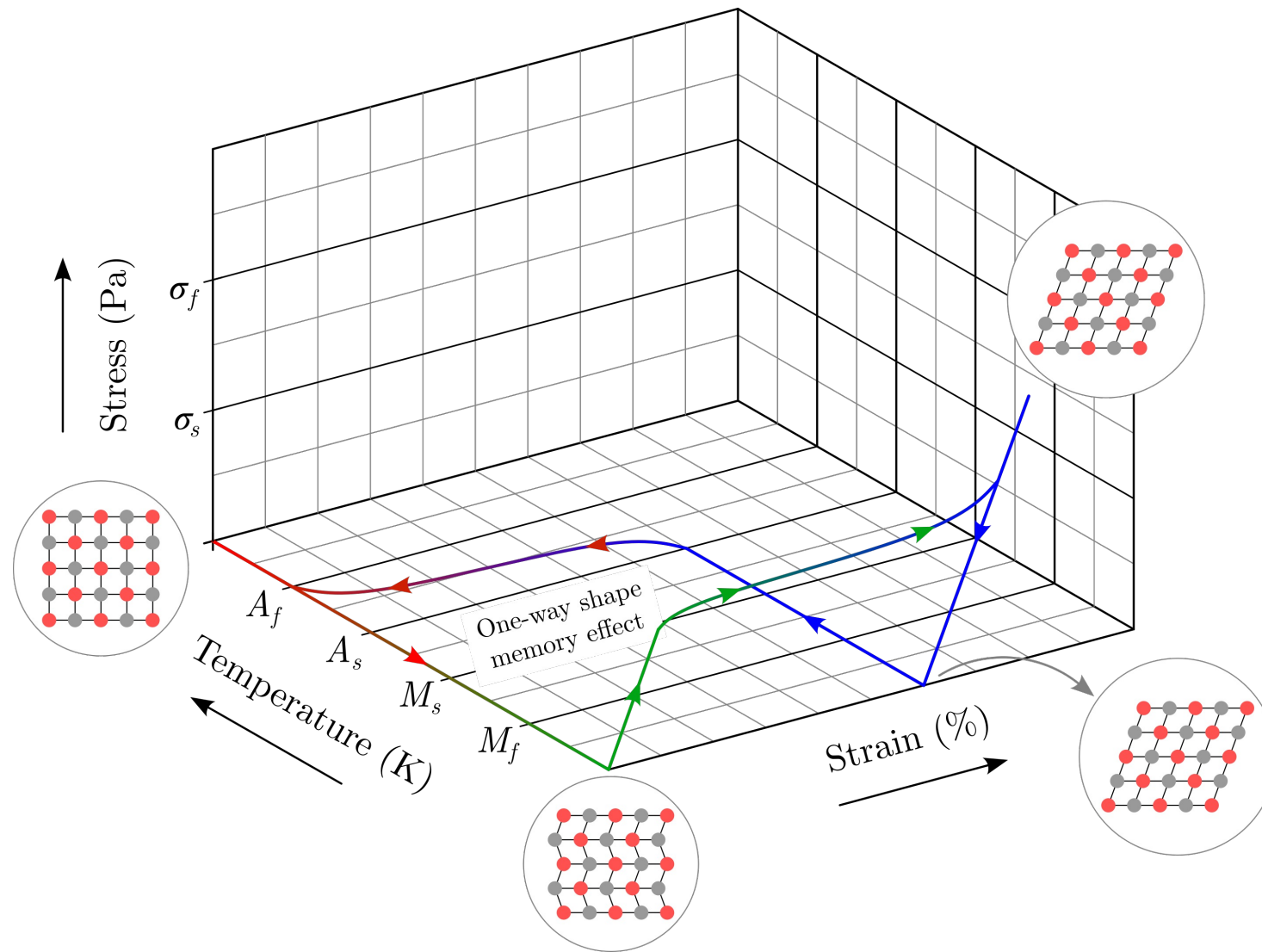


Domínios Magnéticos – Magnetização Espontânea

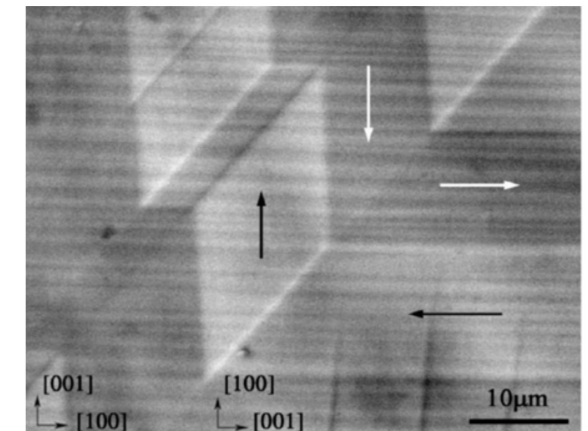
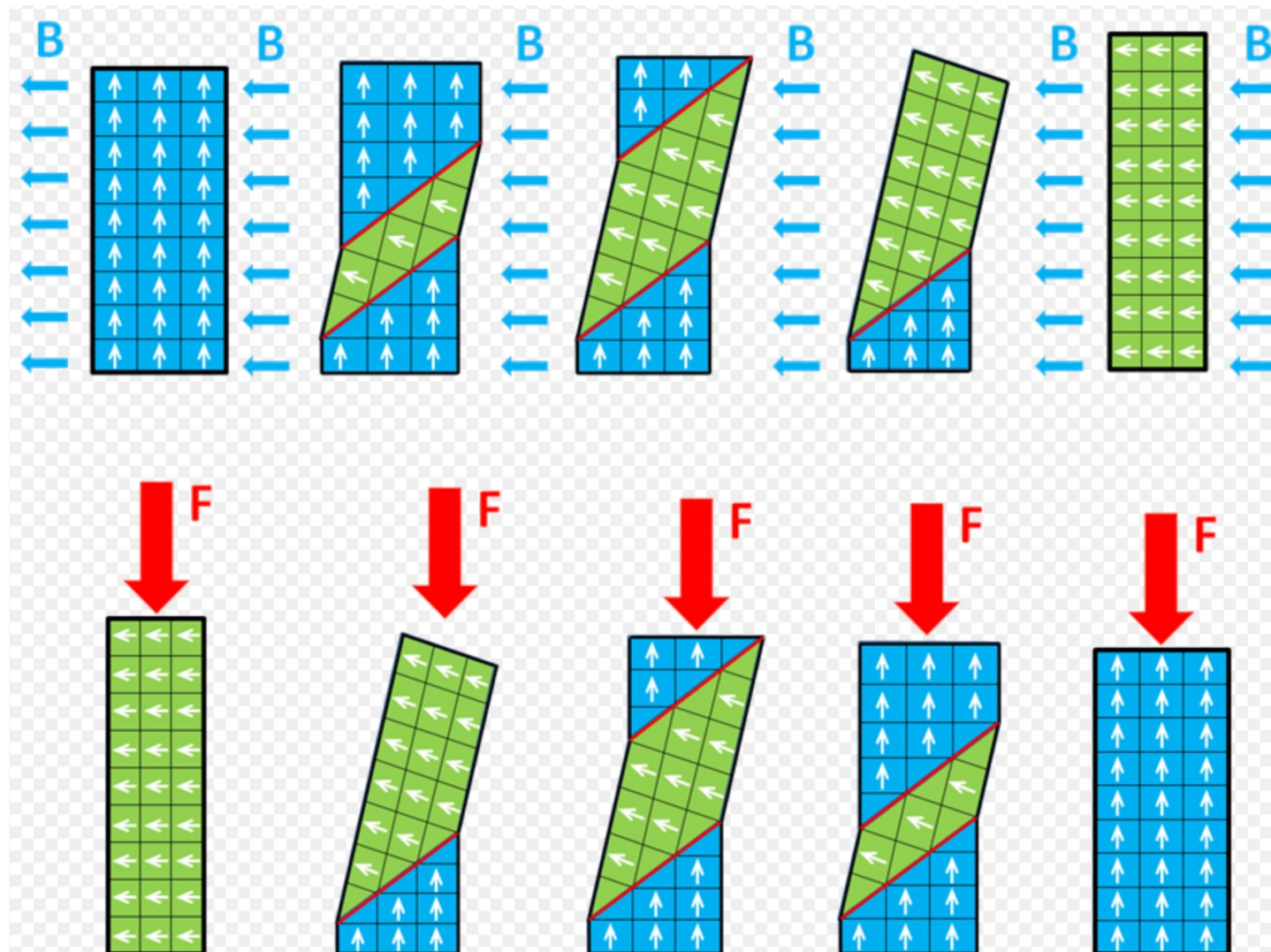


Lagoudas (2008)

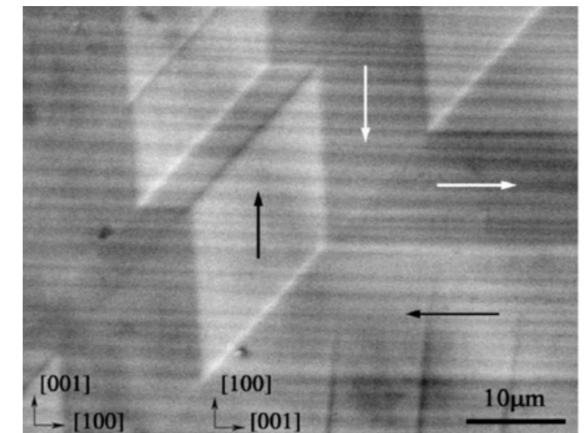
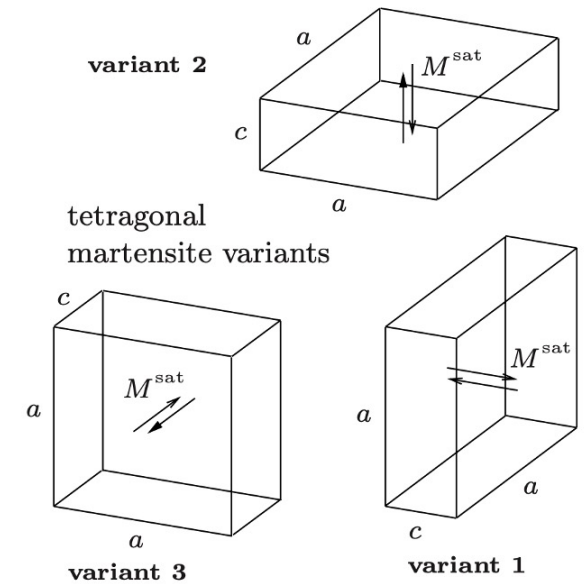
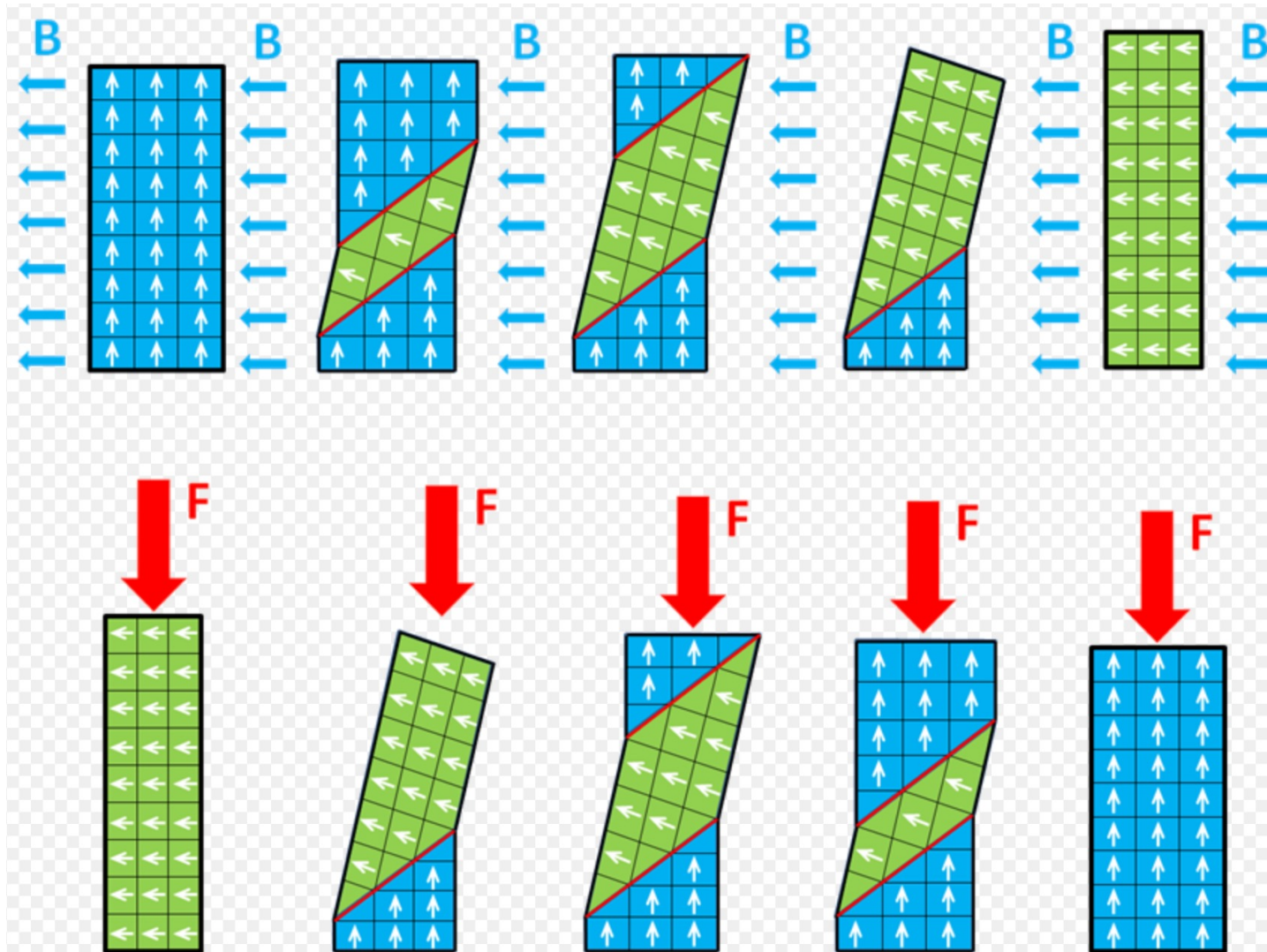
Efeito Memória de Forma Termomecânico



Mecanismo de Reorientação Martensítica



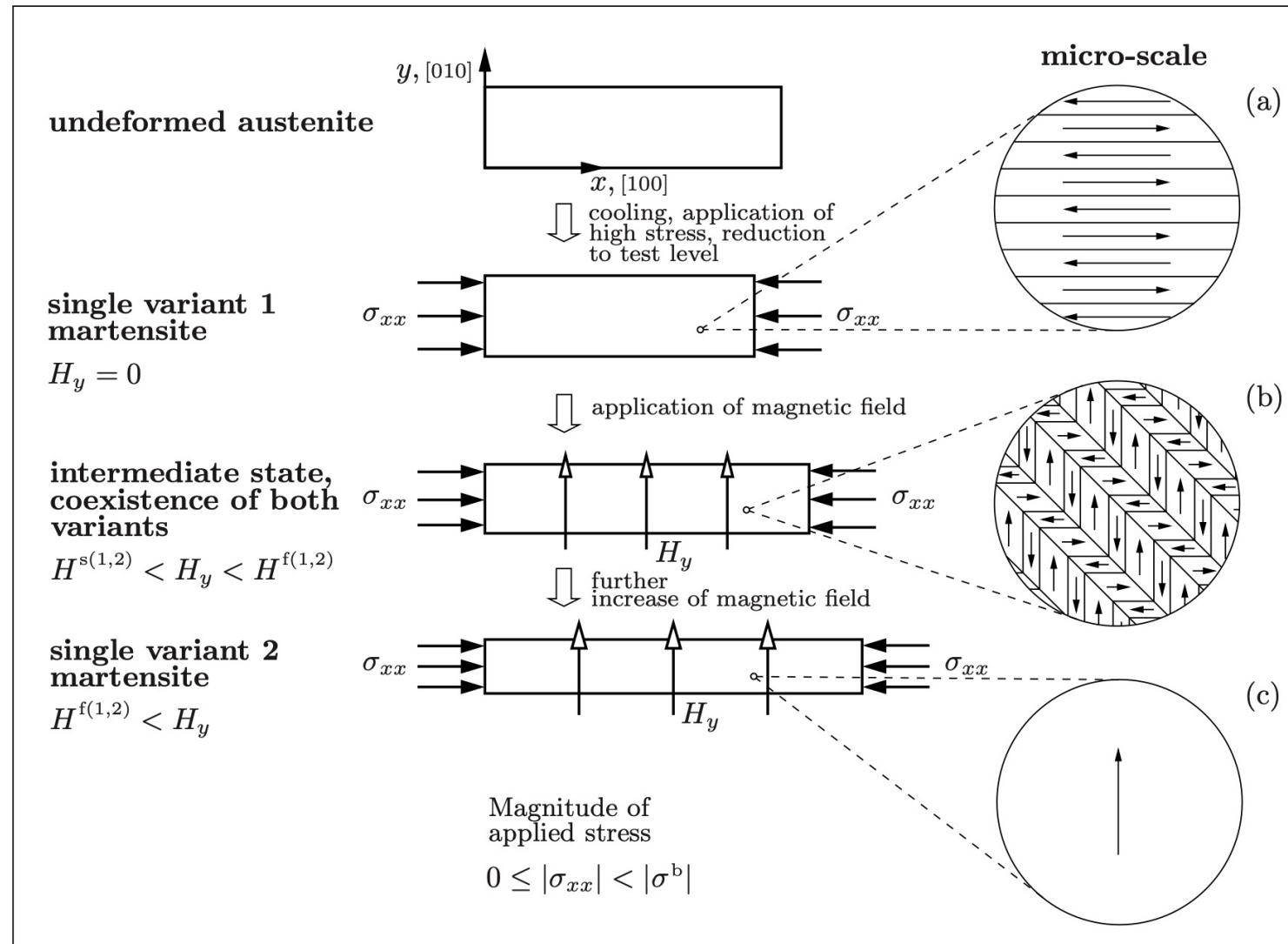
Mecanismo de Reorientação Martensítica



Reorientação de Matensita por Campo Magnético



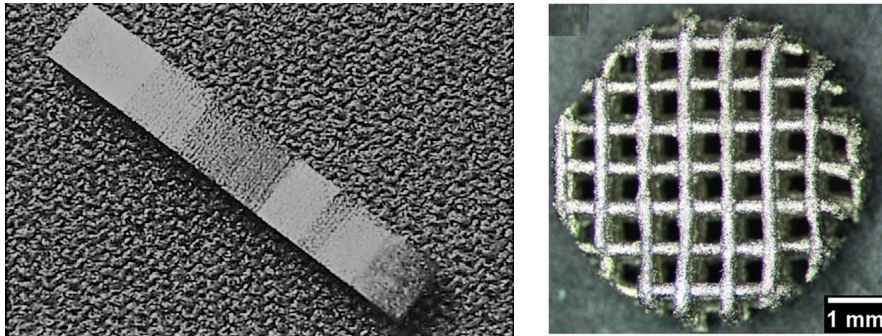
Sequência de Carregamento Termo-Magneto-Mecânica



Lagoudas (2008)

Materiais com Memória de Forma Magnética

Ligas Ni-Mn-Ga



→ Atuação mais rápida que SMAs convencionais

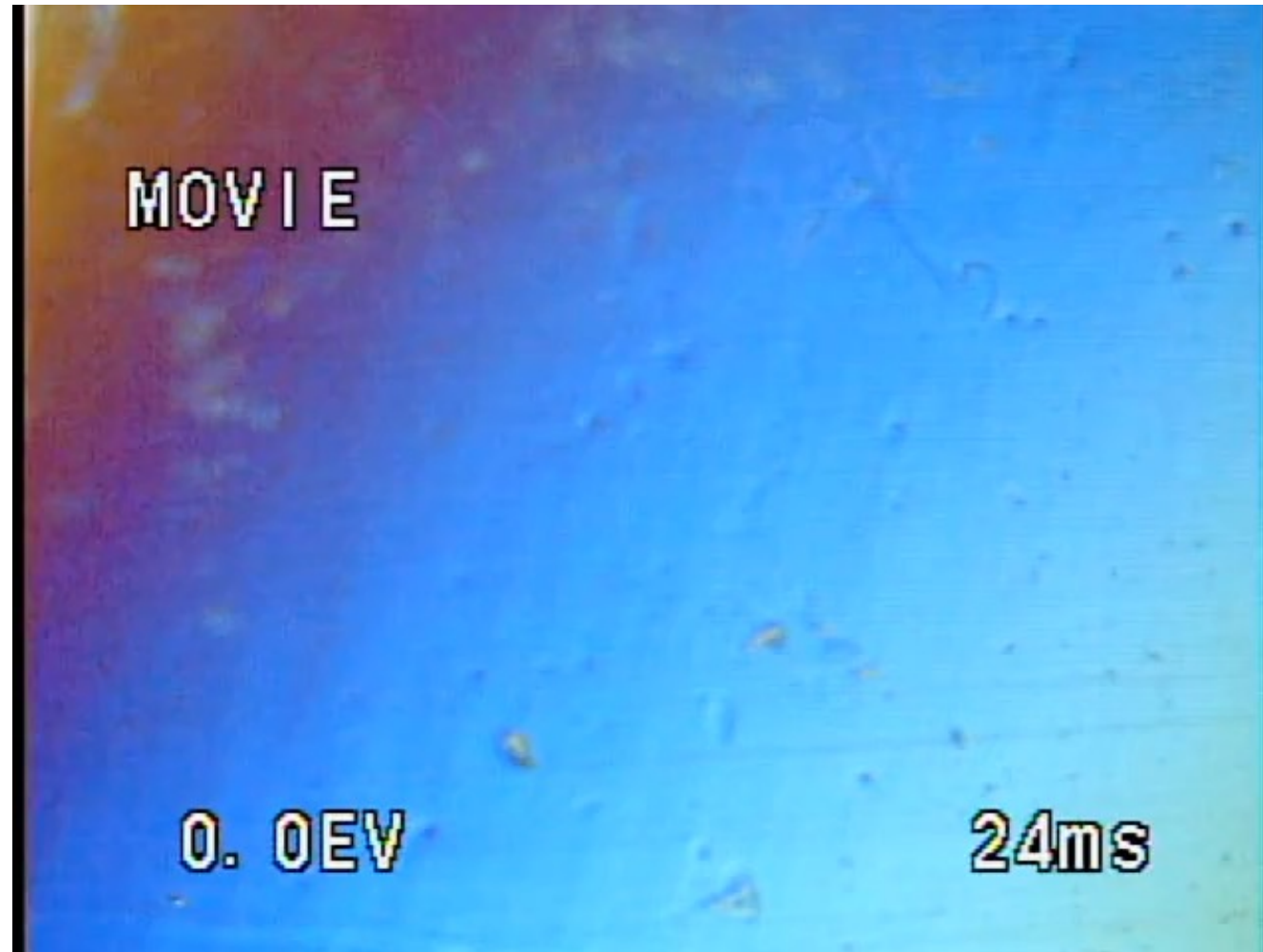
→ Porém, viável apenas abaixo da tensão de bloqueio

Ligas Fe-Pd

Ligas Ni-Co-Mn-In

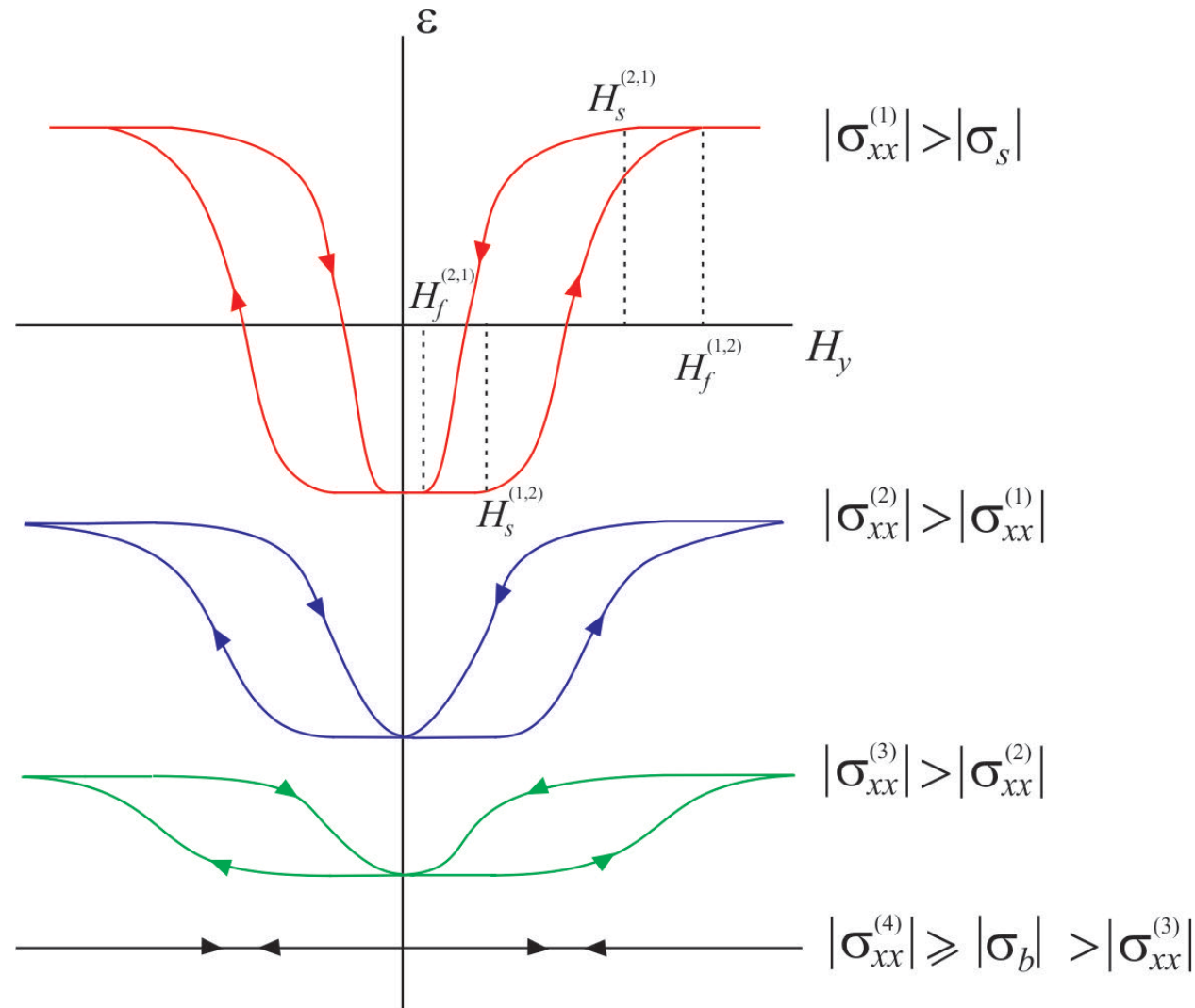
Ligas Ni-Co-Mn-In

Reorientação de Matensita por Campo Magnético

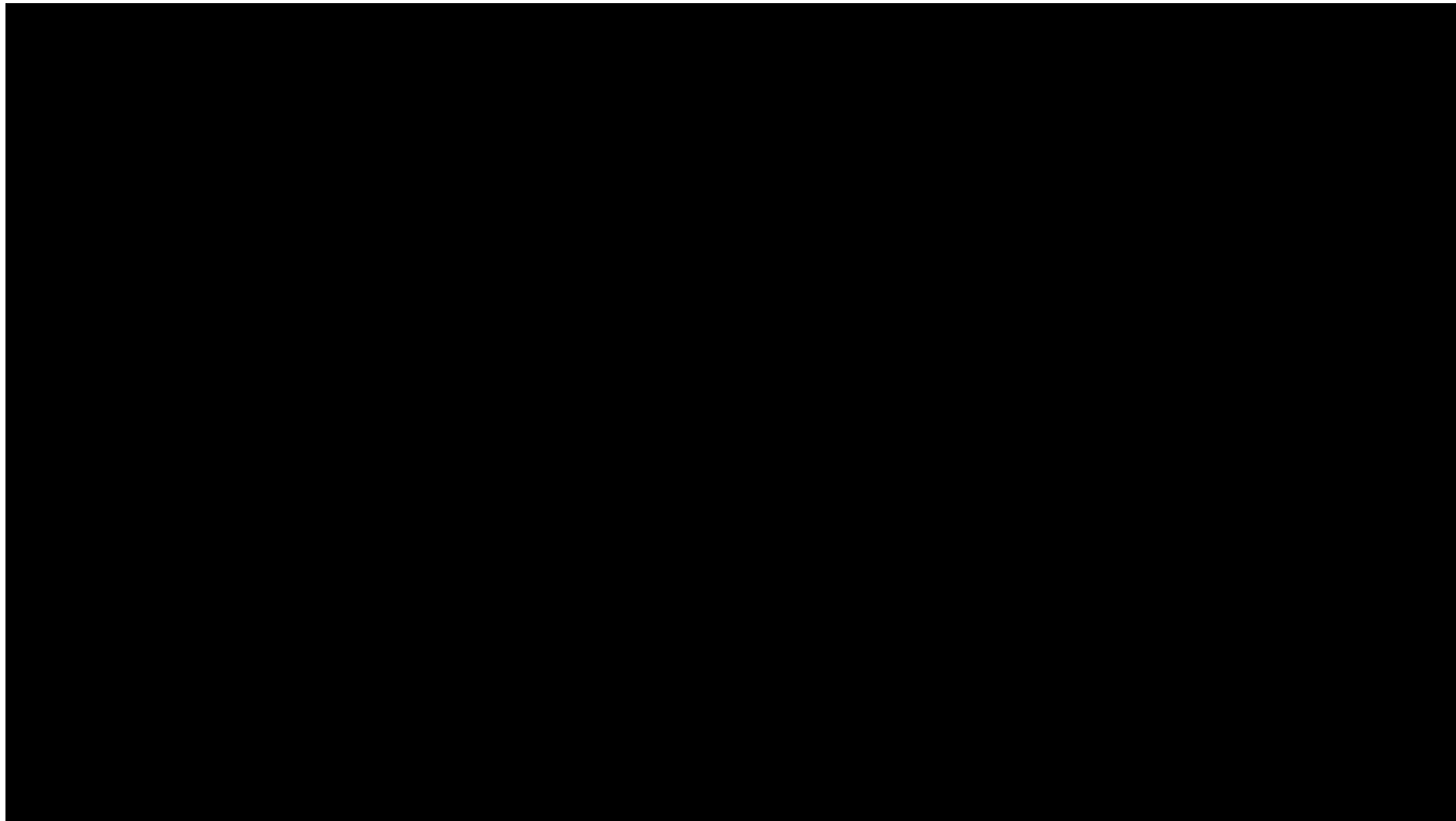


Tsuchiya et al. (2004)

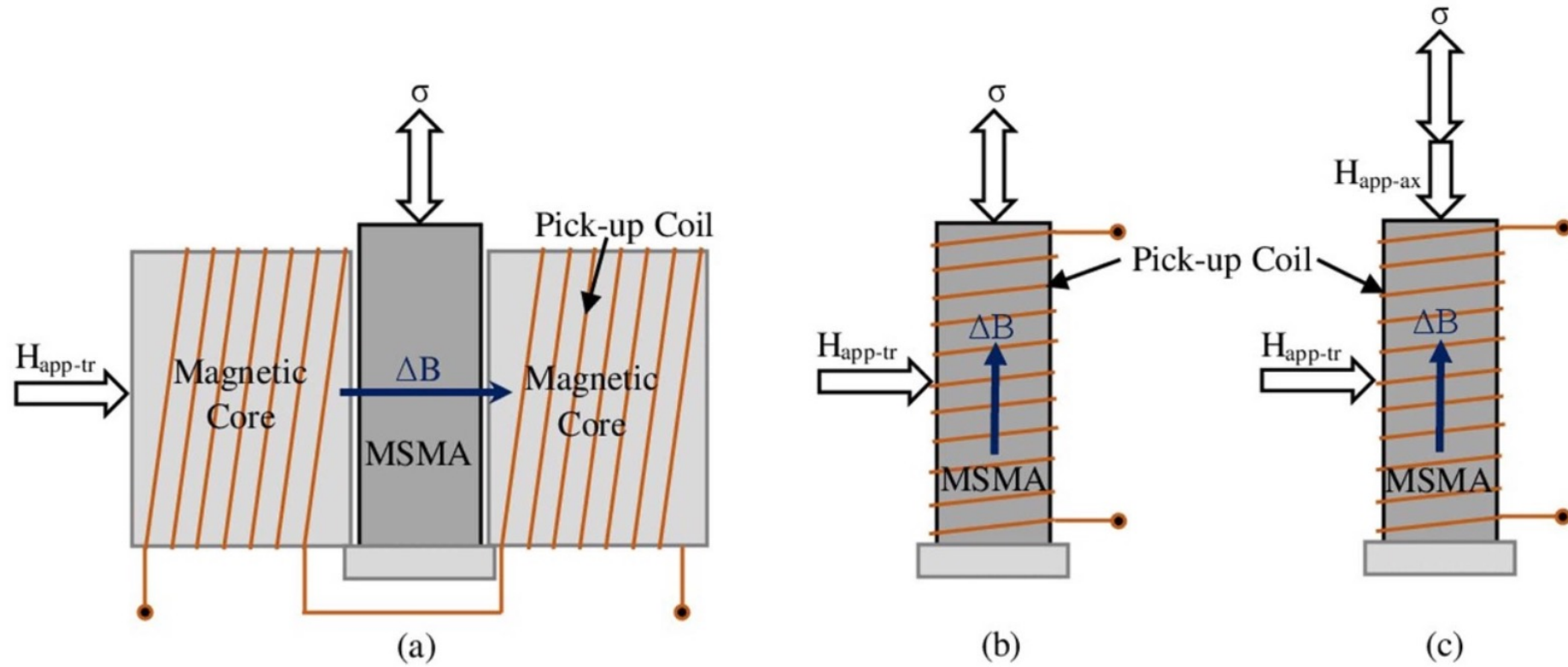
Curva Campo Magnético vs Deformação e Tensão de Bloqueio



Atuadores

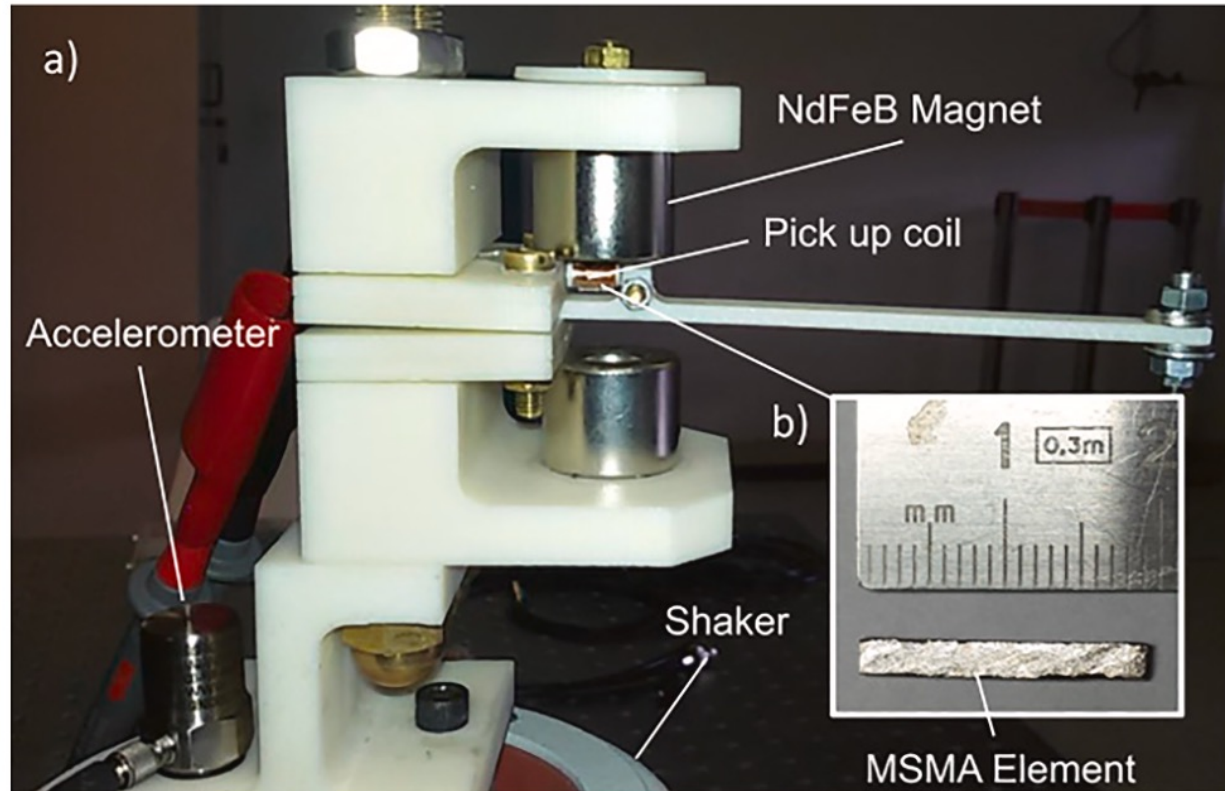


Colheita de Energia

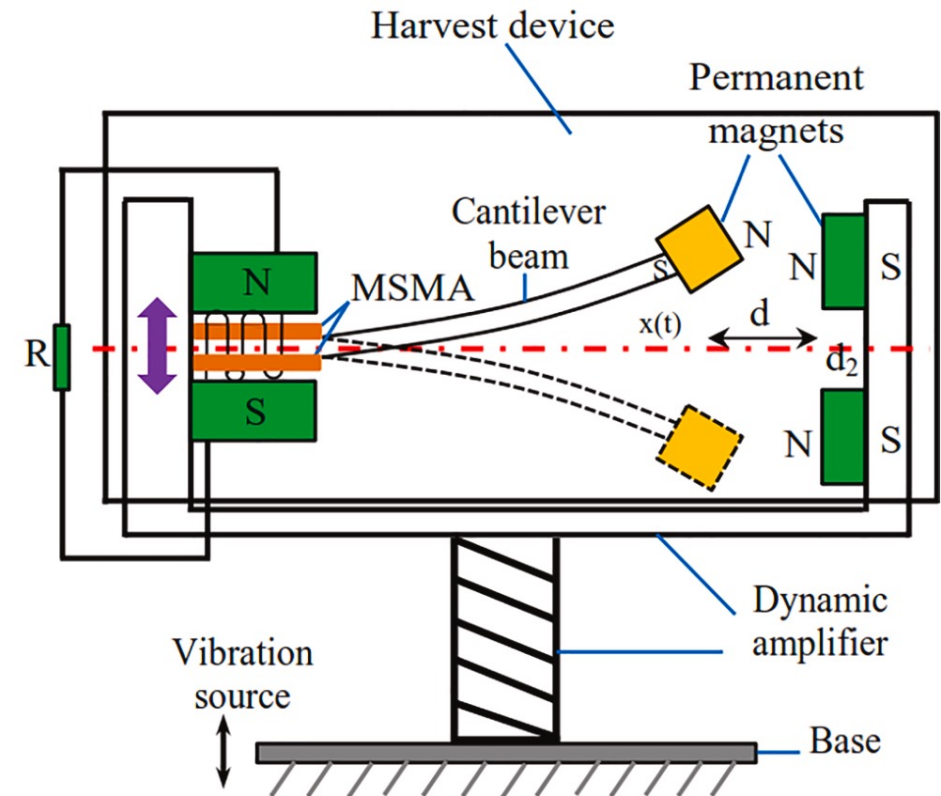


D'Silva et al. (2022)

Colheita de Energia



Farsangi et al. (2017)



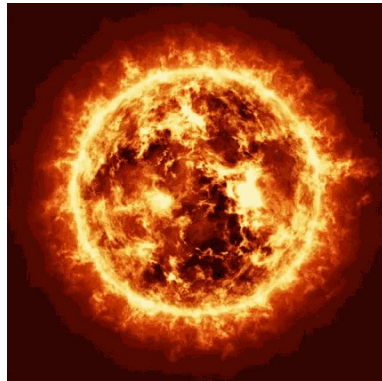
Jing et al. (2020)

Materiais Inteligentes: Acomplamento Multifísico

Mecânico



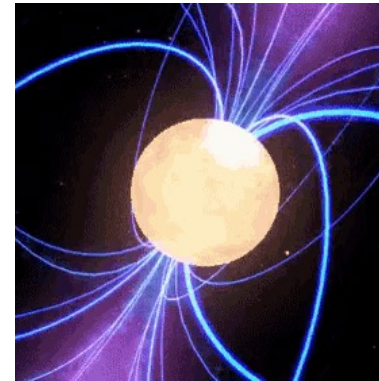
Térmico



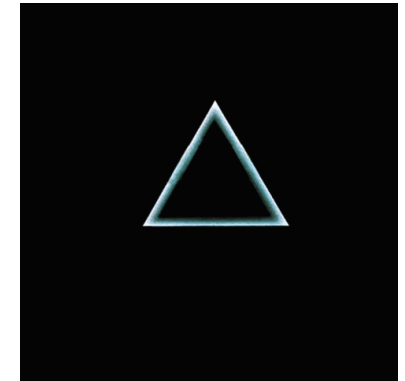
Elétrico



Magnético



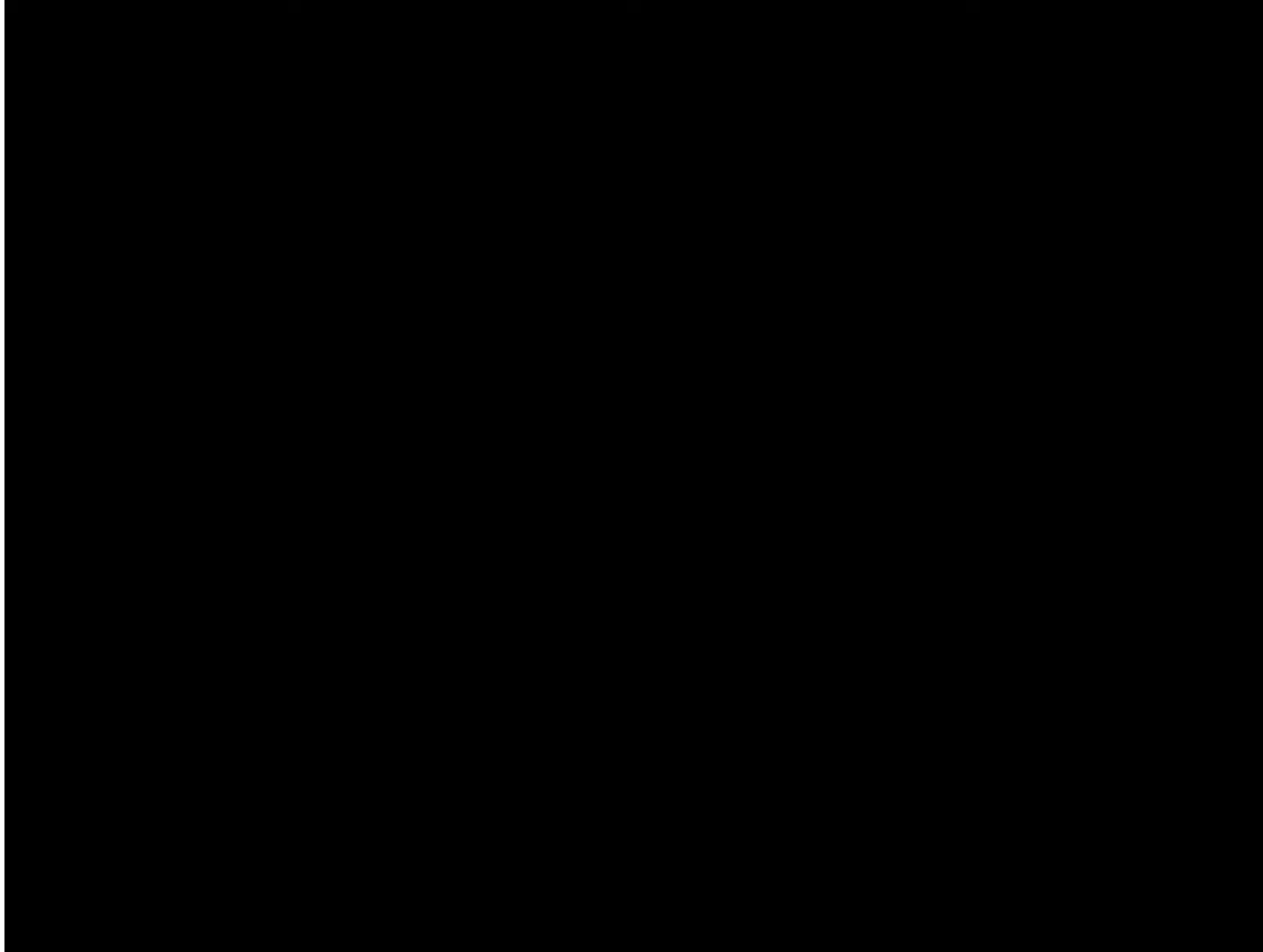
Óptico



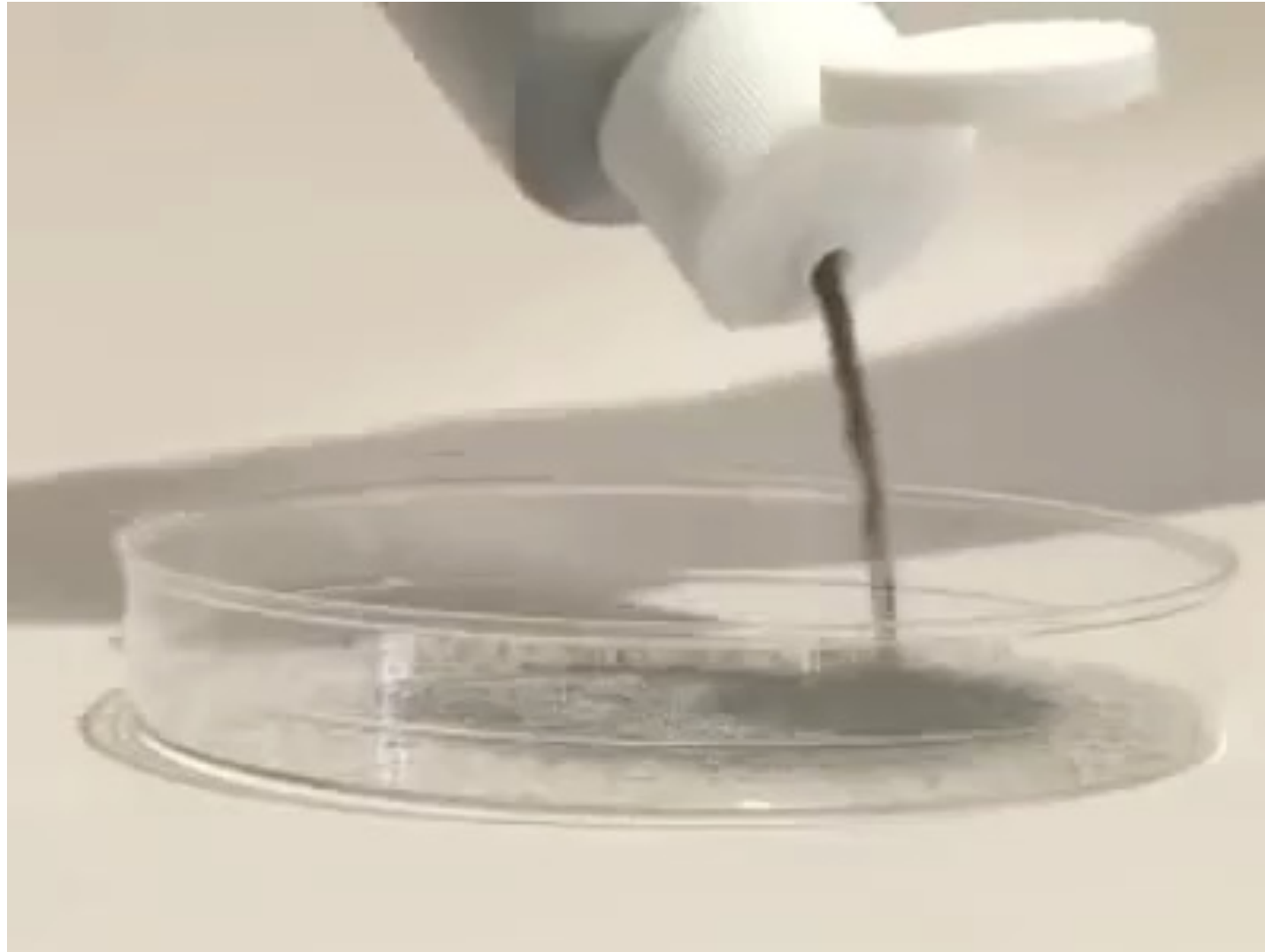
Magnetoestrictivos

Fluidos Magnetoreológicos / Ferrofluidos

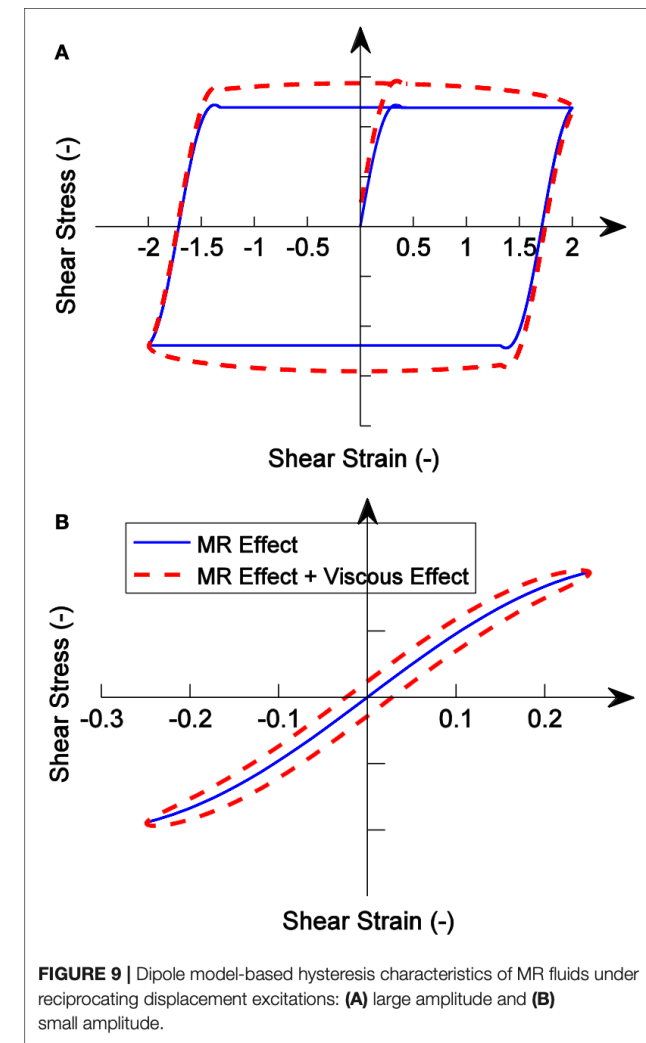
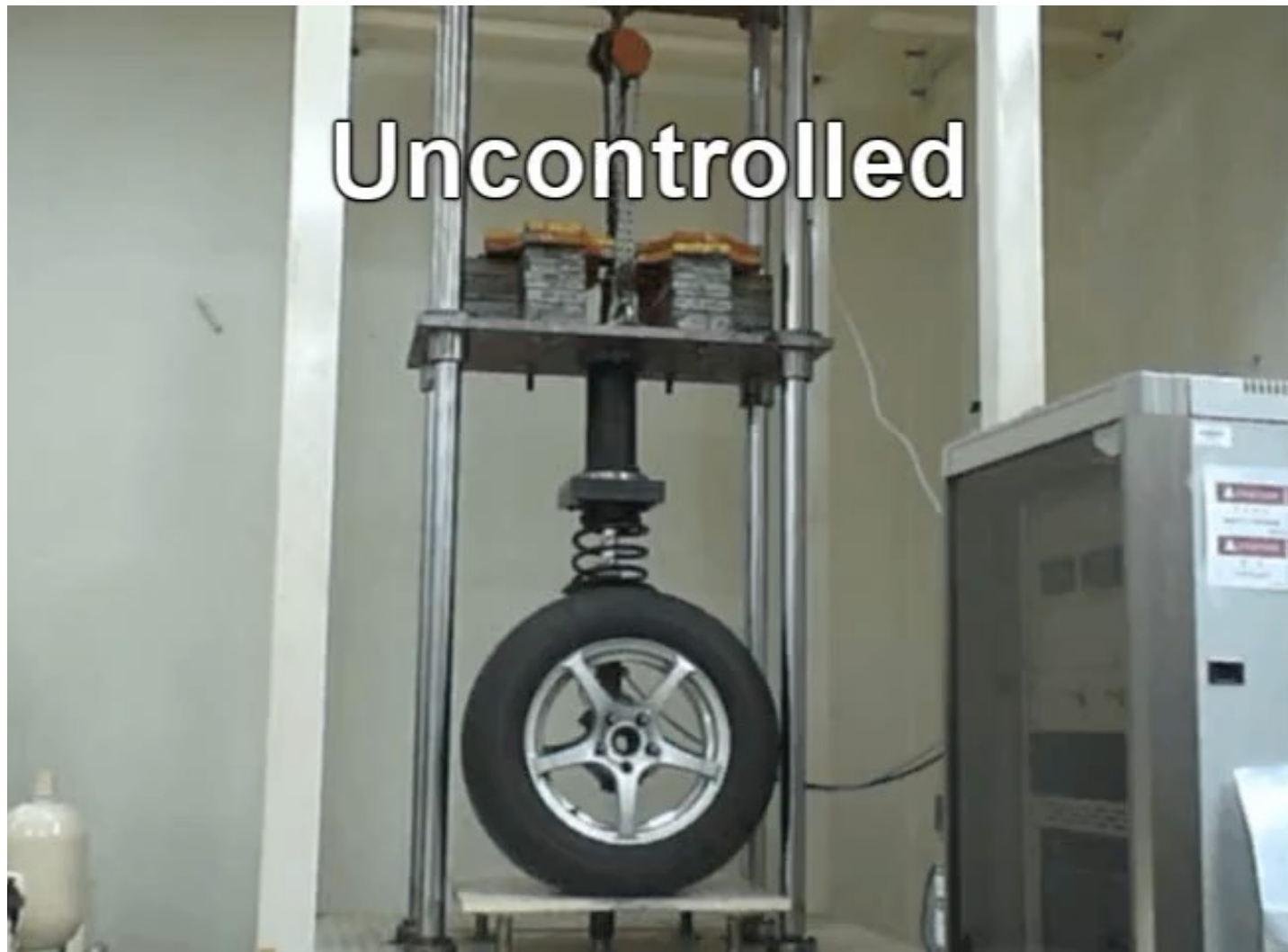
Ferrofluido



Fluido Magnetoreológico



Fluido Magnetoreológico



Bai & Chen. (2019)