High Temperature Shape Memory Alloys

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Characteristic Transformation Temperature Above 100℃

Cu-Al-Nb

Ni-Mn-Ga

Ni-Fe-Ga-Co

U-Nb

Cu-Al-Ag

Ti-Ni-Pd

Ru-Ta

Ti-Ni-Pt

Ni-Mn-Ti

Ti-Pt-Ir

Ti-Mo

Ti-Nb-Pd

Cu-Al-Ni-Mn

Ni-Ti-Hf

Ni-Ti-Zr

Ru-Nb

Ti-Pt

Ni-Mn

Ni-Al-Fe

Co-Al

Co-Si

Cu-Al-Ni

Ti-Pd

Co-Ni-Ga

Ti-Nb

Ni-Al

Co-Ni-Al

Zr-Cu-Ni-Co

Ni-Ta

Ti-Au

Fe-Mn-Si

Pt-Co

Cu-Al-Nb

Ni-Mn-Ga

Ni-Fe-Ga-Co

U-Nb

Cu-Al-Ag

Ti-Ni-Pd

Ru-Ta

Ni-Mn-Ti

Ti-Pt-Ir

Ti-Ni-Pt

Ti-Mo

Ti-Nb-Pd

Cu-Al-Ni-Mn

Ni-Ti-Zr

Ni-Ti-Hf

Ru-Nb

Ti-Pt

Ni-Mn

Ni-Al-Fe

Co-Al

Co-Si

Cu-Al-Ni

Ti-Pd

Co-Ni-Ga

Ti-Nb

Ni-Al

Co-Ni-Al

Zr-Cu-Ni-Co

Ni-Ta

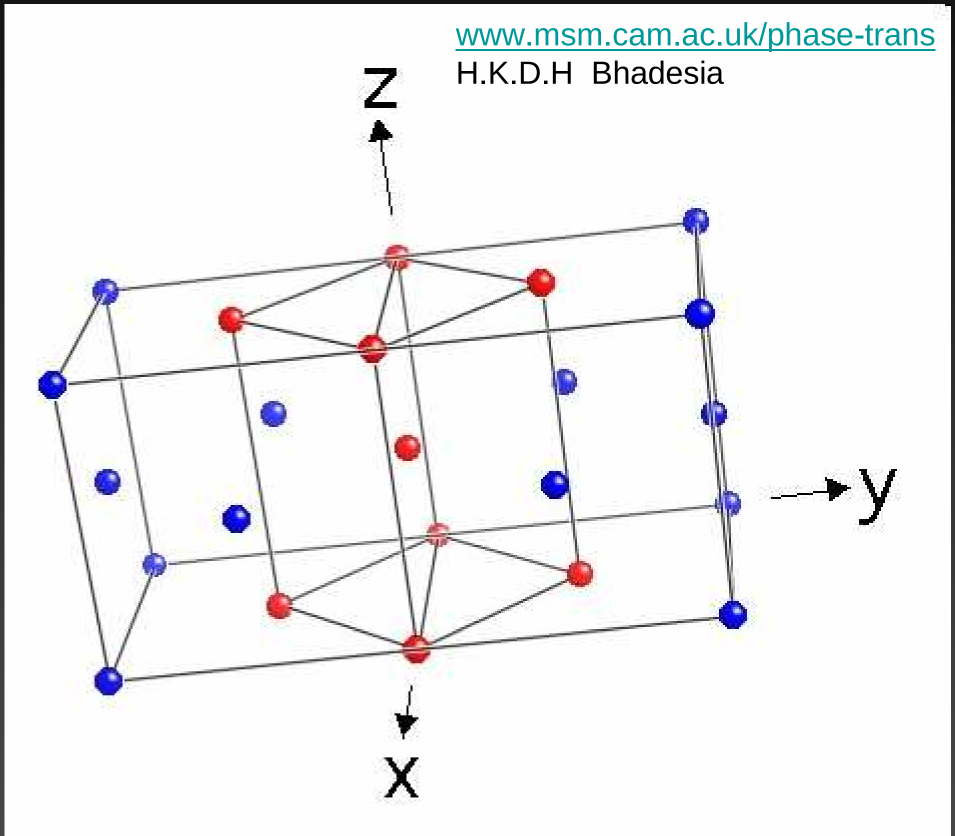
Ti-Au

Fe-Mn-Si

Pt-Co

Total Recoverable strain in polycrystal is limited by inherent properties of the material

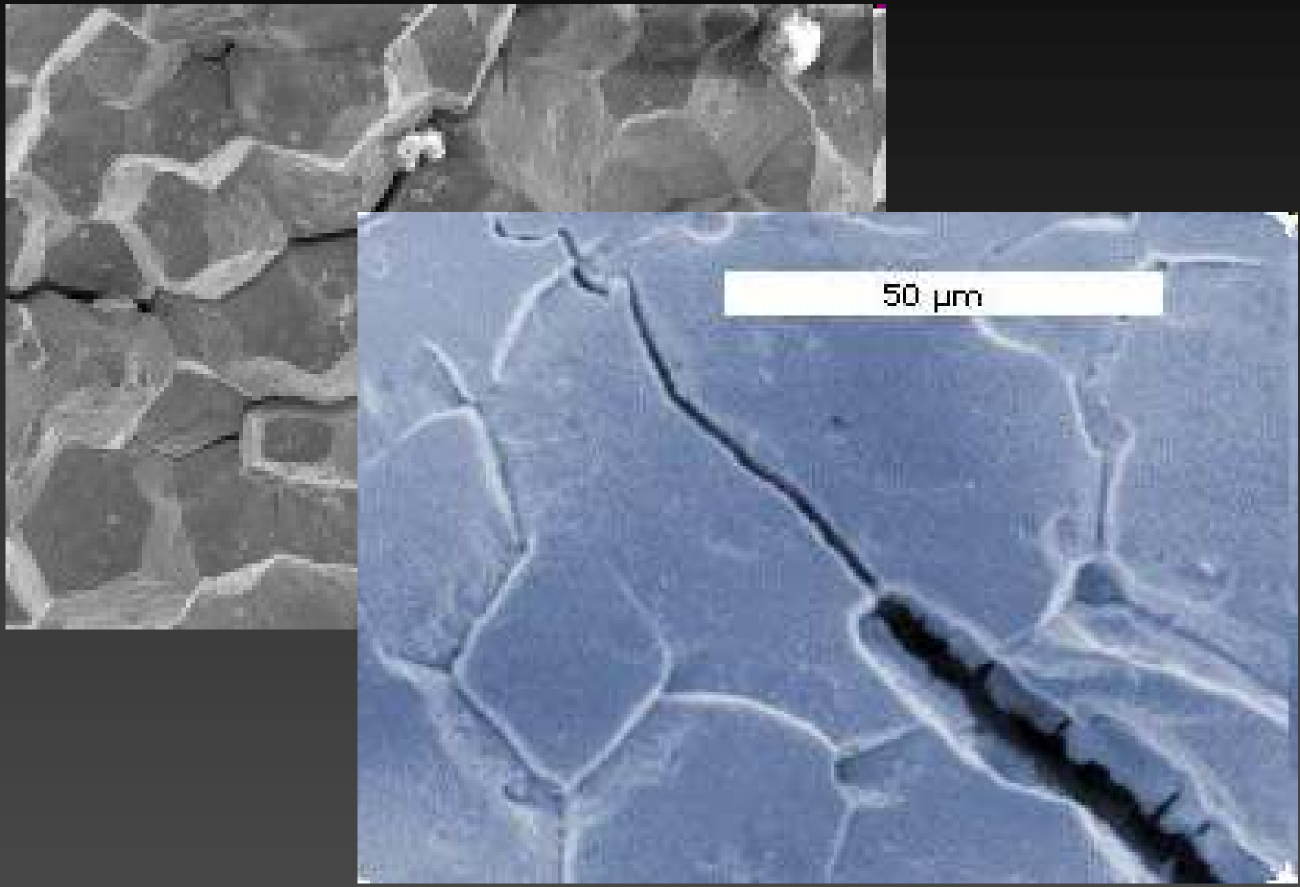
Processing allows us to move closer to that limit



Structure

Ni-Al
Ni-Mn
Co-Ni-Al

Ductility

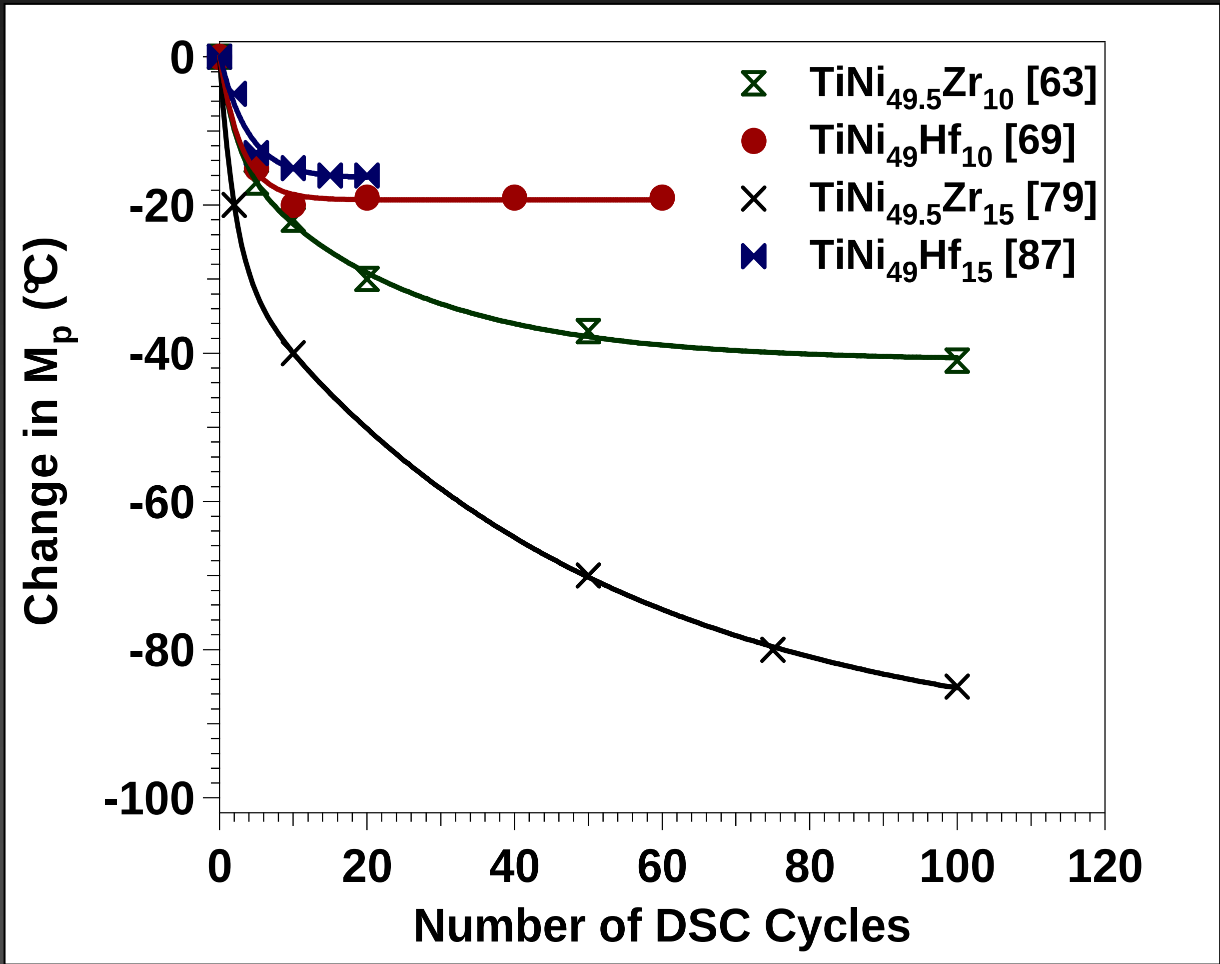


Ni-Al	Co-Ni-Al
Cu-Al-Ni	Ru-Nb
Ni-Mn-Ga	Ta-Nb

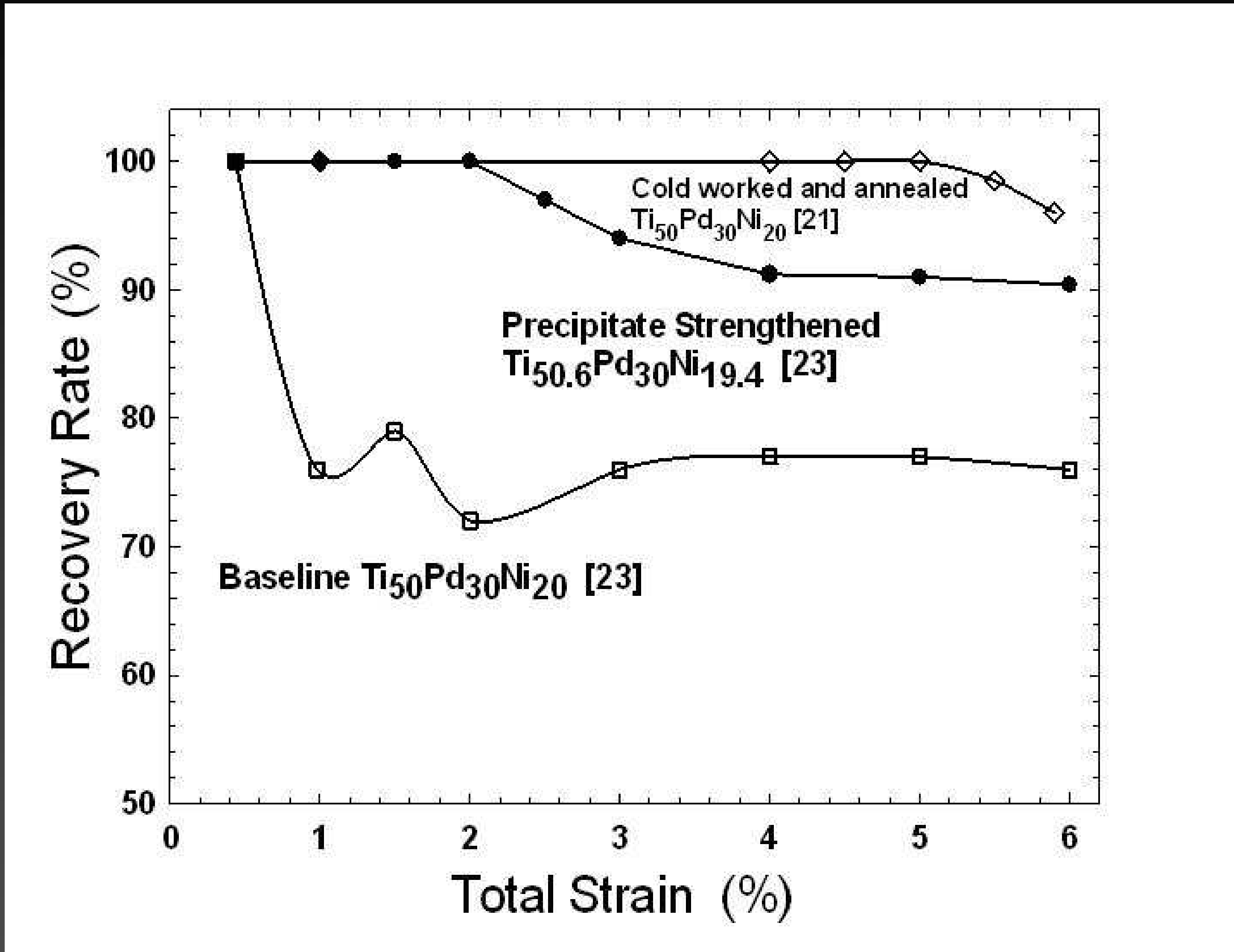
Instability

Phase

Cyclic



Ni-Al
Ni-Mn
Cu-Al-Ni
Ni-Ti-Zr



Reduction of Plasticity!

Ti-Ni-Pt

Ti-Ni-Au

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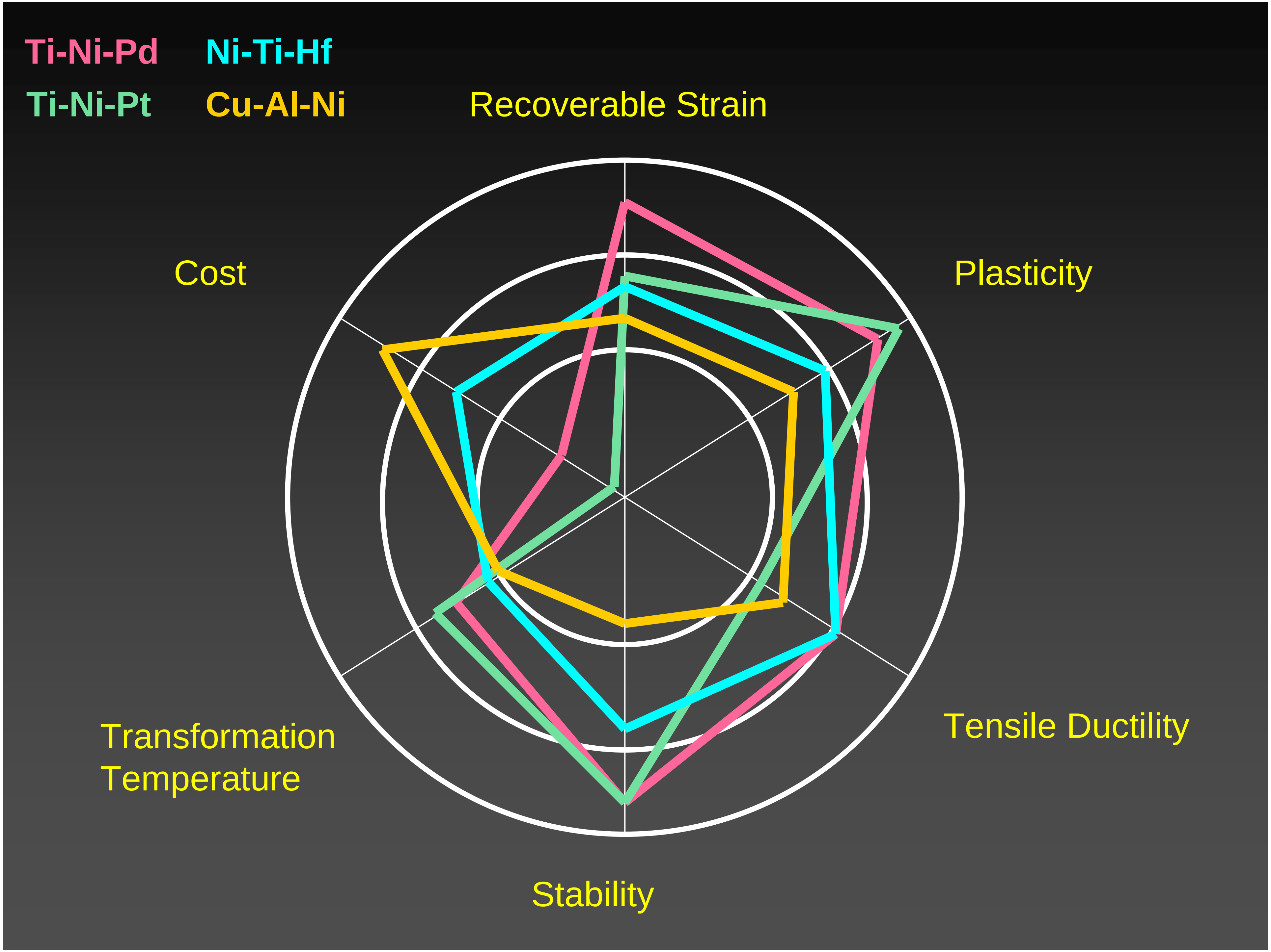
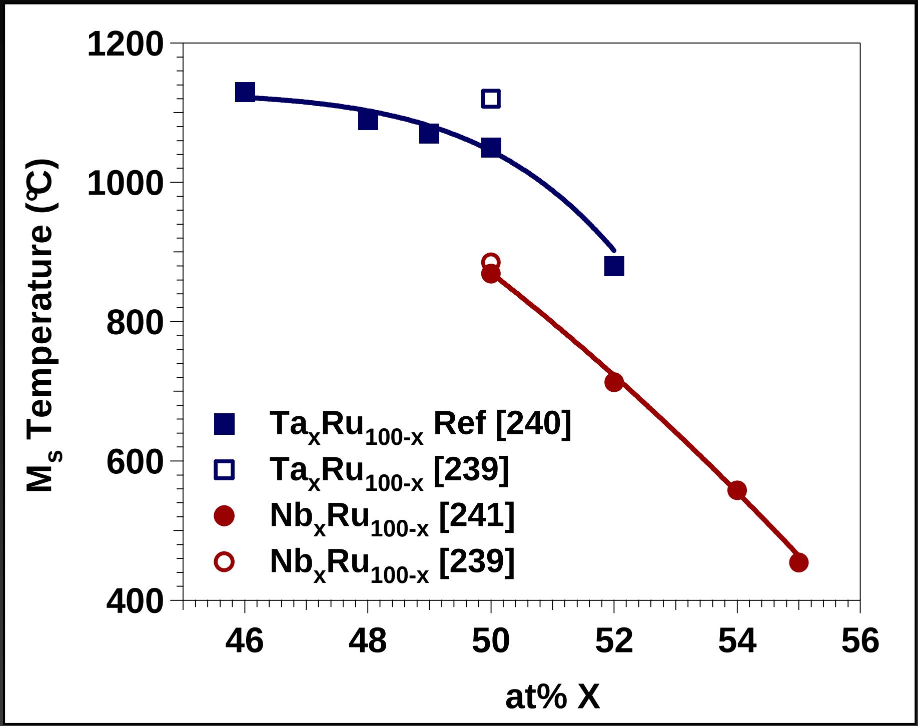
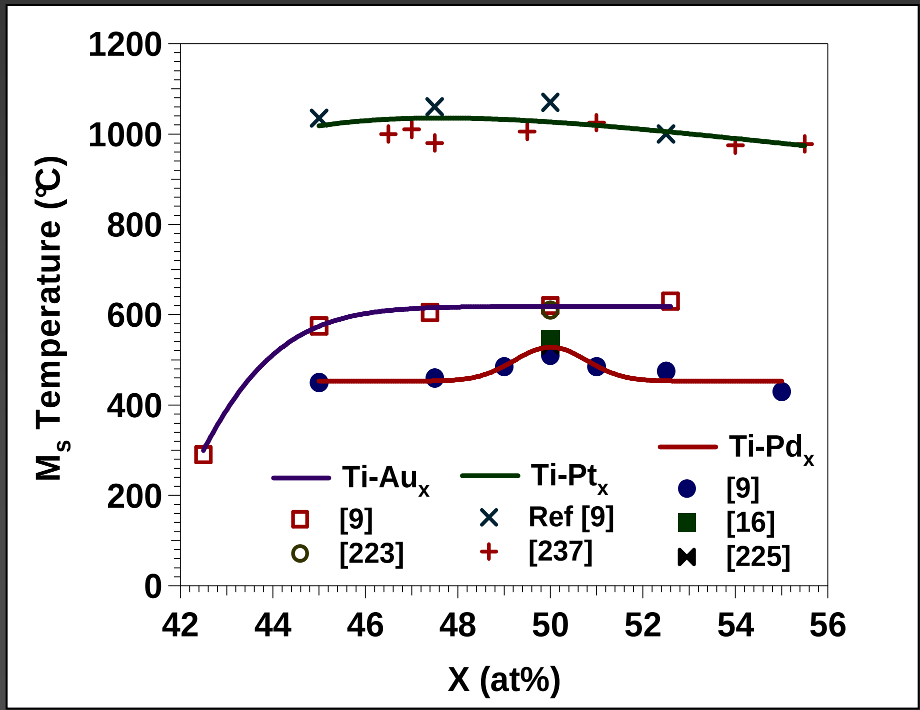
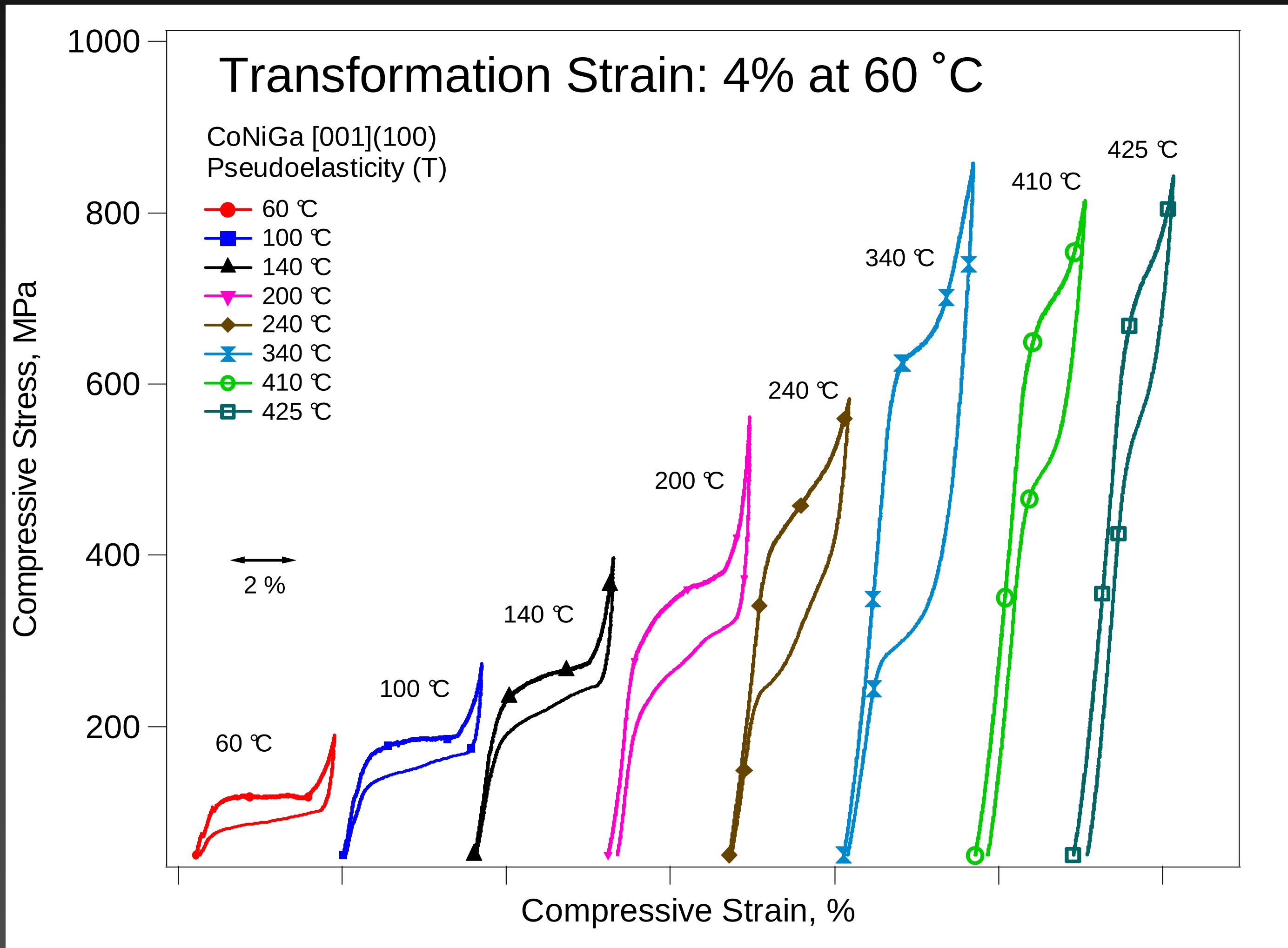
Ti-Ni-Pd


Ti-Ni-Pd
Ni-Ti-Hf
Ti-Ni-Pt
Cu-Al-Ni
Recoverable Strain
Plasticity
Tensile Ductility
Stability
Transformation Temperature
Cost

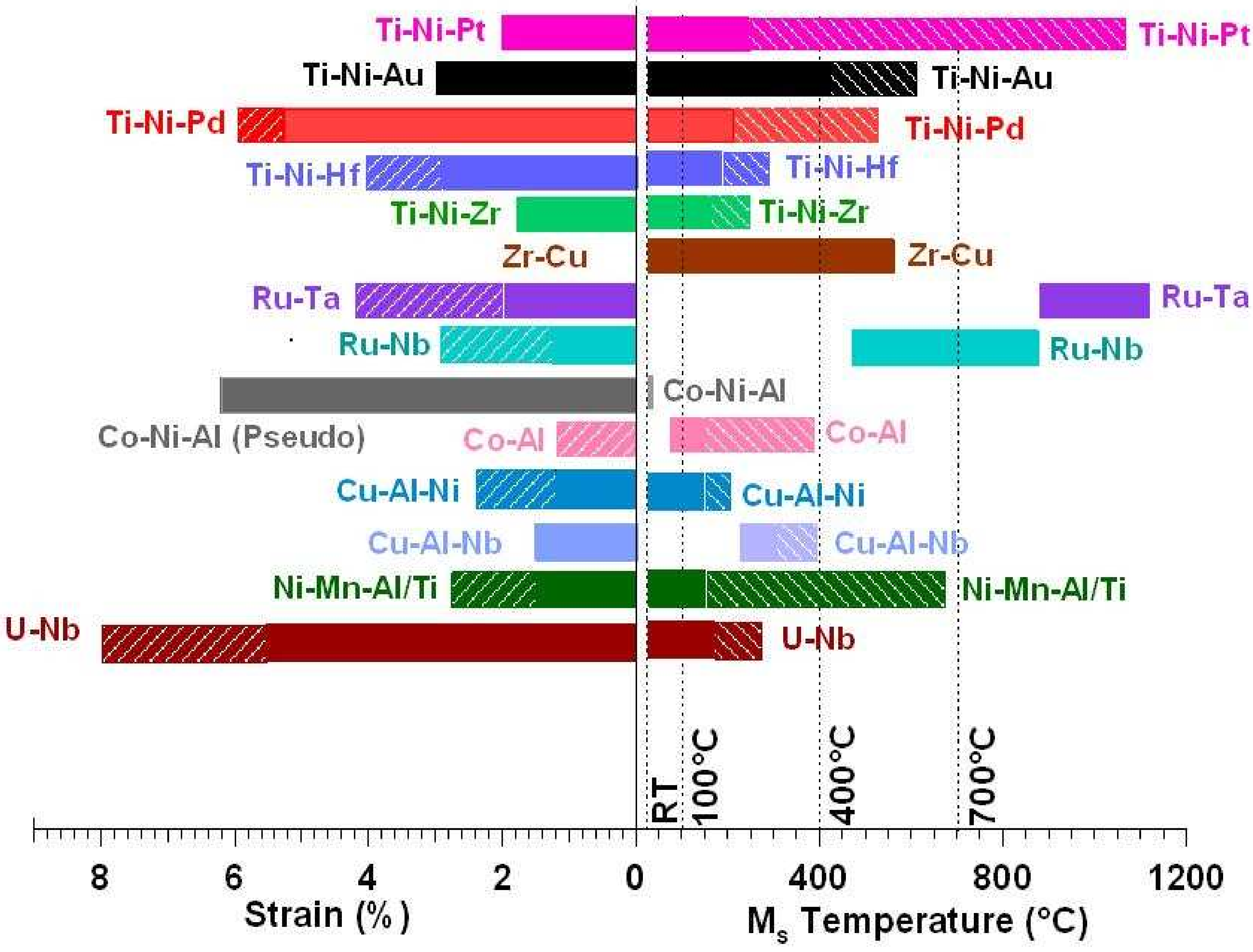
The Ultra-High Temperature Shape Memory Alloys





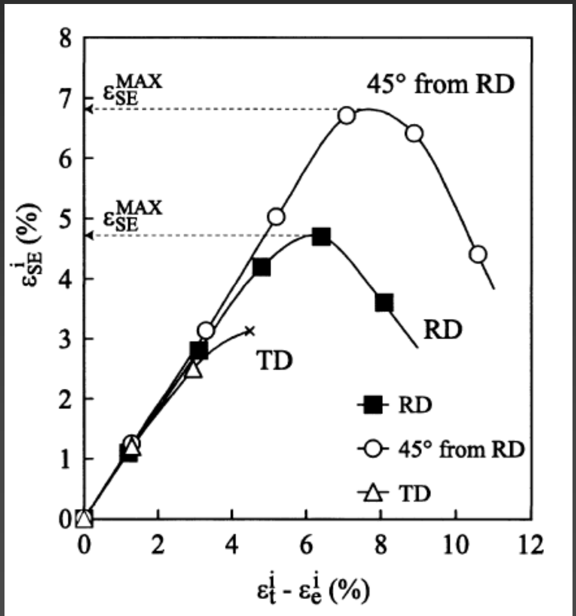


High Temperature Superelasticity



Ti-Ni-Pt
Ti-Ni-Au
Ti-Ni-Pd
Ti-Ni-Hf
Ti-Ni-Zr
Zr-Cu
Ru-Ta
Ru-Nb
Co-Ni-Al
Co-Ni-Al (Pseudo)
Co-Al
Cu-Al-Ni
Cu-Al-Nb
Ni-Mn-Al/Ti
U-Nb
RT
100°C
400°C
700°C
8
6
4
2
0
400
800
1200
Strain (%)
M_s Temperature (°C)

We know a great deal about HTSMAs, but we also know very little



Oxidation resistance?

Creep behavior?

Actuation behavior?

Texture effect?

Consistency in experiments?

Alloy (at% unless noted)	Transformation Temperature Range in Celsius[α]	Shape Memory Characteristics[β]	Pseudoelastic Characteristics[β]	Max Known Work Output (Jcm^{-3})	Tensile Ductility[γ]	Thermal Hysteresis (℃)	Maximum Operational Temperature (℃)
$Ti_{50}Ni_{20}Pd_{30}$	215-269	(*Tension*, 170℃) 5.4% Strain **100% recovery**	(*Tension*, 262℃) 4% Strain **90% recovery**	8-11	(170℃) 6%+	25.7	550 [#]
$Ti_{50.6}Pd_{30}Ni_{19.4}$	224-270	(*Tension*, 25℃) 7.2% Strain **100% recovery**	(*Tension*, 285℃) 4% Strain **100% recovery**	8-11	(170℃) 6%+	35	
$Ti_{50}Ni_{30}P_{t20}$	232-297	(*Tension, Thermal Cyle* 10-380℃) 2.6% strain **100% recovery**		9	(220℃) 3.4%	20	500 [&]
$Ti_{36}Ni_{49}Hf_{15}$	148-231	(*Tension*, 80℃ or *Bending*, 100℃) 3% Strain **100% recovery**			(25℃) 7%	60	
$Ti_{34.9}Ni_{49.8}Zr_{15.3}$	139-222	(*Bending*, 25℃) 1.8% Strain at external fiber **100% recovery**		16.8 (thin film)	5-7%	54	
$Cu_{80}Al_{11.9}Ni_{5}Mn_{2}Ti_{1}$ (wt%)	133-193	(*Tension*, 155℃) 3% Strain **80% recovery**			(25℃) 4%	21.5	200*
$Cu_{70.96}Al_{12}Ni_{4}Mn_{4}B_{0.04}$	41-96		(*Tension*, 200℃) 5% Strain **90% recovery**		(150℃) 5.5%		
$Co_{90}Al_{10}$	134-283	(*Bending*, 25℃) 2% Strain at external fiber **90% recovery**			High	121	

Alloy (at% unless noted)	Transformation Temperature Range in Celsius[α]	Shape Memory Characteristics[β]	Pseudoelastic Characteristics[β]	Max Known Work Output (Jcm^{-3})	Tensile Ductility[γ]	Thermal Hysteresis (℃)	Maximum Operational Temperature (℃)
$Co_{37.6}Ni_{32.9}Al_{29.5}$	-57-(-26)		(*Compression*, 170℃) 5% Strain **100% recovery**		Poor	15.5	
$Ni_{42.5}Mn_{50}Ti_{7.5}$	200-240	(*Torsional-Bending*, *Thermal Cyle* 160-280℃) 3.9% strain **90% recovery**			Poor	20	400[#]
$Ni_{54}Mn_{25}Ga_{21}$	231-335	(*Compression*, 25℃) 10% Strain **70% recovery**			Very Poor	85	
$Zr_{42.3}Cu_{29.9}Ni_{11}Co_{10.2}Ti_{6.6}$	67-247	(*Compression*, 177℃) 8% strain **44% recovery**				70	
$U_{86}Nb_{14}$	77-212	(*Tension*, 25℃) 7% Strain **97% recovery**			(25℃) 17%	35	
$Ti_{50}Pd_{50}$	539-591	(*Tension*, 25℃) 10% Strain **88% recovery**			Good	40	500[#]
$Ti_{50}Au_{50}$	575-650	(*Tension*, 25℃) 3% Strain **100% recovery**				35	
$Ti_{50}Pt_{25}Ir_{25}$	1068-1190		(*Compression*, 1200℃) 10% Strain **40% recovery**			66.5	
$Ru_{50}Ta_{50}$	1040-1070	(*Compression*, 900℃) 4% Strain **50% recovery**			Poor	20	
$Ru_{50}Nb_{50}$	869-919	(*Bending*, 800℃) 4.2% Strain **88% recovery**			Poor	20	

Where to go from here?

Thank you

System	Transformation Temperature Range (℃)	Transformation Phases	Comments
Ti-Ni-Pd	100-530	B2 (BCC) - B19 (Orthorhombic) > 10% Pd B2 (BCC) - B19' (Monoclinic) <10% Pd	- High work output, large recoverable shape memory strain, most commercial ready - High materials cost, irrecoverable strain difficult to eliminate in load-bias tests
Ti-Ni-Pt	100-1100	B2 (BCC) - B19 (Orthorhombic) > 10% Pt B2 (BCC) - B19' (Monoclinic) <10% Pt	- High Work output, full recovery possible in load-bias tests, good environmental resistance - Very high materials cost
Ni-Ti-Hf	100-400+	B2 (BCC) - B19' (Monoclinic) <15% Hf B2 (BCC) - B19 (Orthorhombic) > 20% Hf	- Reasonable shape memory behavior, relatively low materials cost - Large hysteresis, formability difficulty
Ni-Ti-Zr	100-250+	B2 (BCC) - B19' (Monoclinic) <15% Zr B2 (BCC) - B19 (Orthorhombic) > 20% Zr	- Relatively low materials cost - Stable phase precipitation, large change in transformation temperatures during cycling
Cu-Al-Ni	100-400	β(BCC-L21) - α'(9R Orthorhomic) <11% Al β(BCC-L21) - 18R Orthorhomic 11-13% Al β(BCC-L21) - γ'(2H Tetragonal) >13% Al	- Low cost, reasonable shape memory and pseudoelastic behavior - Brittle in tension - Stable phase precipitation near 200℃, reodering c auses shift in transformation temperature in quenched specimen
Cu-Al-Nb/Ag	100-400	β(BCC-L21) - α'(9R Orthorhomic) <11% Al β(BCC-L21) - 18R Orthorhomic 11-13% Al β(BCC-L21) - γ'(2H Tetragonal) >13% Al	- Good workability - Poor shape memory response
Co-Al	100-400	γ(FCC) - ε(HCP)	- Good workability - Non-thermoelastic, large hysteresis
Co-Ni-Al/Ga		(B2 BCC) - γ(L10 non-modulated)	- High Temperature Pseudoelasticity, very high yield strength - Poor tensile ductility

Ni-Al	100-300	B2 (BCC) - β' (3R L102 BCT) <37% Al B2 (BCC) - 7R (L102 BCT) >37% Al	- Low materials cost, low hysteresis - Very poor ductility and shape memory response, stable phase precipitation from martensite near 250C
Ni-Mn	100-670	B2 (BCC) - θ(L10 tetragonal)	- Ternary alloy allows for low hysteresis and improved shape memory response - Poor tensile ductility, loss of shape memory effect above 400℃
Ni-Mn-Ga	100-400	L21 - 2M (tetragonal)	- Very poor tensile ductility
Zr-Cu	100-600	B2 (BCC) - B19 (Orthorhombic) B2 (BCC) - Cm (Orthorhombic)	- Good ductility - Poor shape memory response, large hysteresis
Ti-Nb	100-200	β(BCC) - α''(Orthorhomic)	- Excellent ductility and workability - Precipiation of omega phase at about 120℃
U-Nb	100-200	γ (BCC) - γ0 (tetragonal) >15.4% Nb γ (BCC) - α'' (orthorhombic) <15.4% Nb	- Good ductility, good shape memory response, large transformation strain - suspect to oxidation, contains uranium
Ti-Au	100-630	B2 (BCC) - B19 (Orthorhombic)	- High materials cost
Ti-Pd	100-510	B2 (BCC) - B19 (Orthorhombic)	- Good ductility - Recovery occurs at transformation temperature, high materials cost
Ti-Pt-Ir	990-1184	B2 (BCC) - B19 (Orthorhombic)	- Very high yield strength
Ta-Ru	900-1150	β(BCC) - β''(Monoclinic)	- Small hysteresis, stable microstructurally - Poor oxidation resistance
Nb-Ru	425-900	β(BCC) - β''(Monoclinic)	- Small hysteresis, stable microstructurally - Poor oxidation resistance

Incomplete list of Challenges – NiTiX alloys

- ✓ Low critical stress for slip
- ✓ Unstable thermomechanical response and cyclic instability due to plasticity
- ✓ Viscoplastic behavior in these materials at high temperatures
- ✓ Large thermal and stress hysteresis (NiTiHf, NiTiZr replacing Ti)
- ✓ Low Fracture toughness (NiTiPd, NiTiPt replacing Ni)
- ✓ Lower transformation strain than binary
- ✓ Workability
- ✓ Oxidation resistance
- ✓ Cost