SAND2015-10048C

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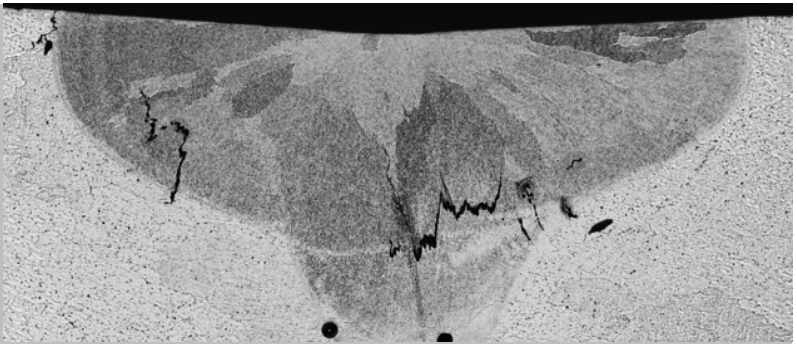
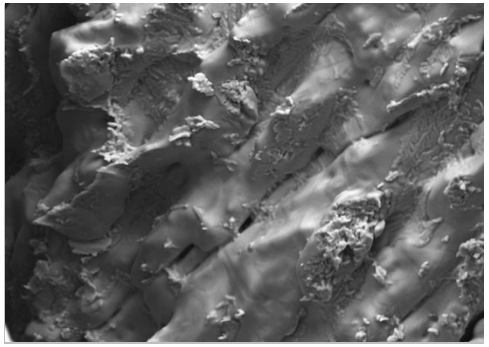
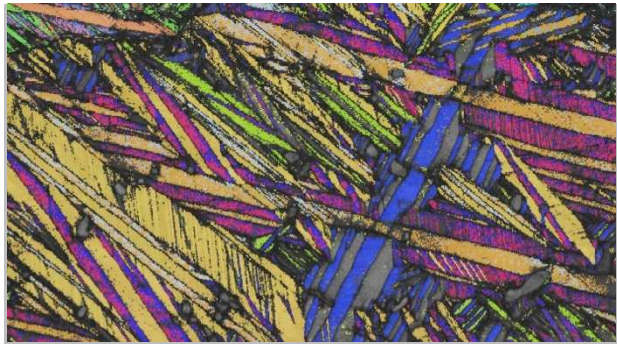

An Assessment of High-Temperature Shape Memory Alloy Weldability

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FABTECH 2015

Nov. 9th, 2015

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

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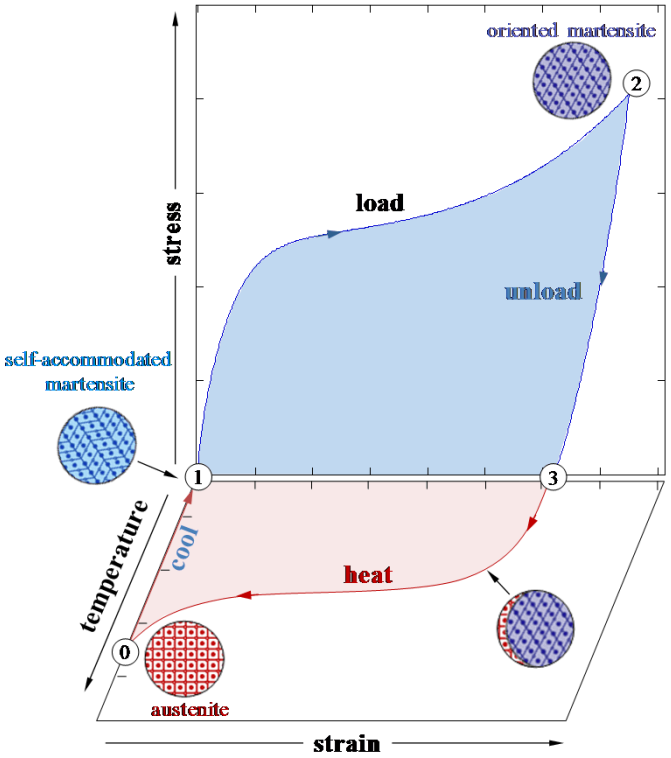
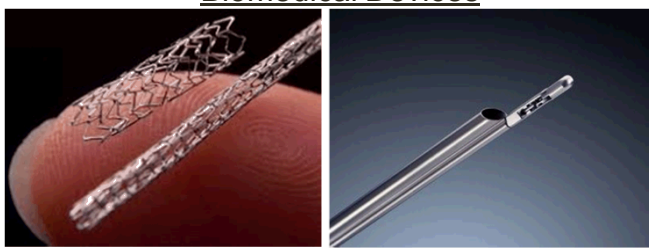
What is a Shape Memory Alloy (SMA)?

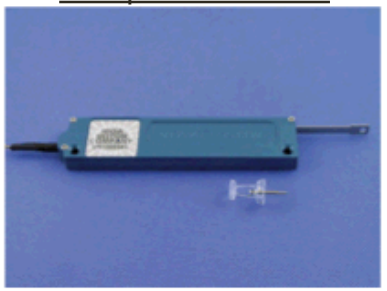
- Unique class of intermetallic alloys that changes shape using a 1st order transformation
- Widely used conventional NiTi intermetallic SMA has functional limitations of ~100ºC
- New high temperature (HT) SMAs being developed to perform >100ºC.



Biomedical Devices

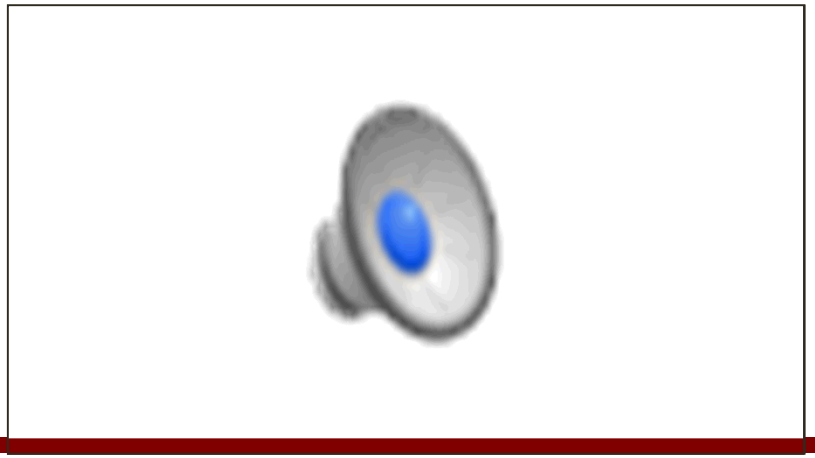


Compact Actuators



Habe et al., Proc of SPIE Vol. 6525 6525C-1 (2007)

Safety Devices



Why Explore the Weldability of Shape Memory Alloys?

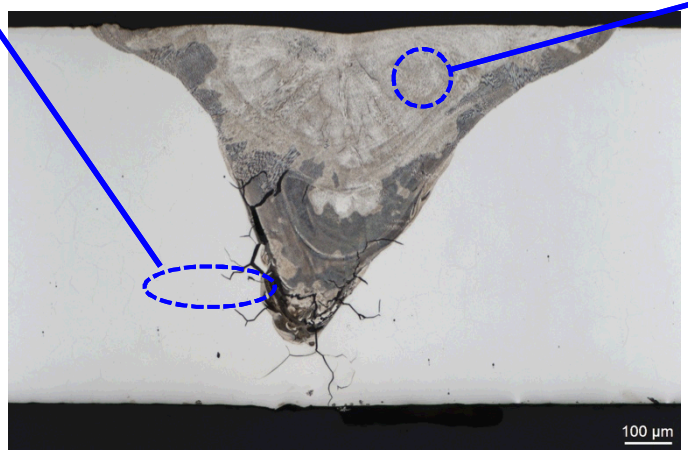
- Weld metallurgical phenomena that determine material weldability has received little attention for SMAs

- Eventual development of robustly welded high-temperature (HT) SMAs in real-world applications requires understanding of weld metallurgy
  - Ternary HTSMAs based on Ni-Ti-X system, X=Hf, Pd, Pt

<u>Heat Affected Zone Weldability Concerns</u>

- Liquation cracking
- Sub-solidus HAZ embrittlement
- Liquid metal embrittlement
- Reheat/Strain-age cracking
- HAZ sensitization
- Lamellar cracking

Fabrication Weldability Considerations for Engineering Alloys



<u>Weld Metal Weldability Concerns</u>

- Solidification cracking
- Weld metal liquation*
- WM Ductility dip cracking*
- Hydrogen-induced cracking

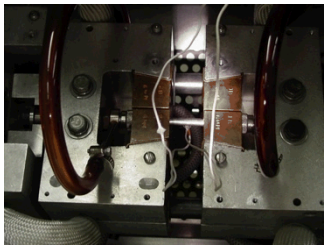
*multi-pass welds

Weldability of SMAs/HTSMAs: A Multi-Technique Approach

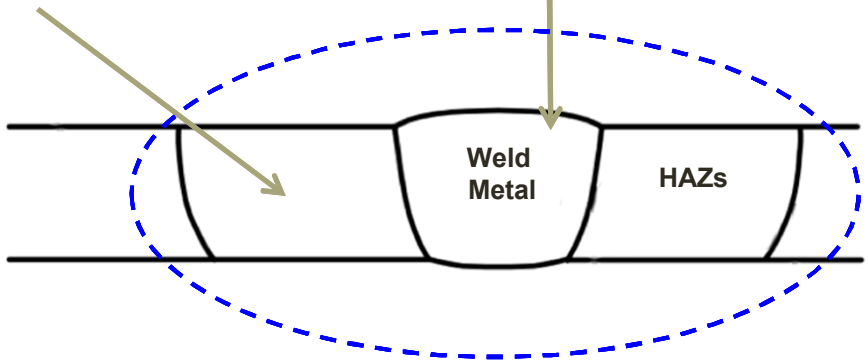
- True assessment of SMA weldability will require an understanding metallurgical behavior governing SMA cracking during welding

- Simplified Ni-Ti binary provides insight into new Ni-Ti-X HTSMAs

#1:
Heat Affected Zone Cracking
Evaluating elevated temperature ductility



Gleeble Thermomechanical Simulator



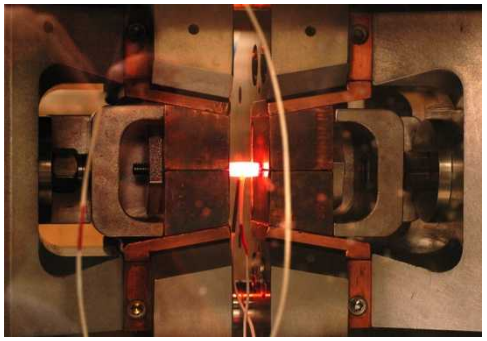
#2:
WM Solidification Cracking
Evaluating SMA/HTSMA susceptibility

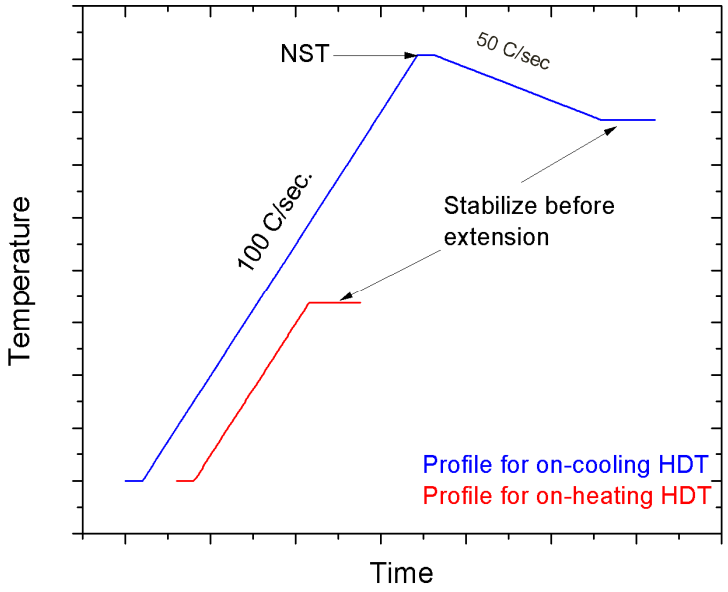
Cast Pin Tear Test Sample

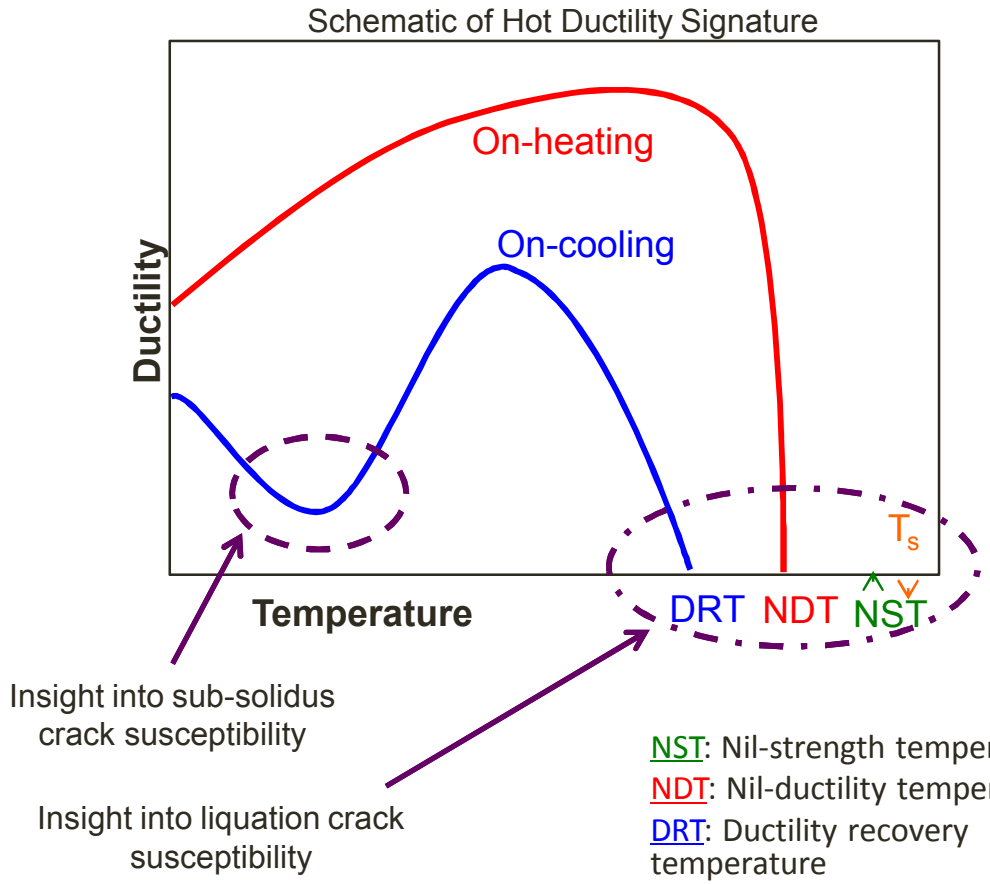
Existing SMA welding studies examine behavior of all weld zones combined

#1: Hot Ductility of SMA HAZs

- High-temperature ductility response of material provides insight into material weldability
- HAZ cracking generally associated with exhaustion of available ductility

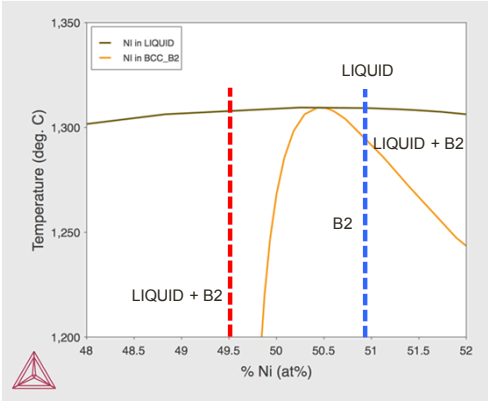


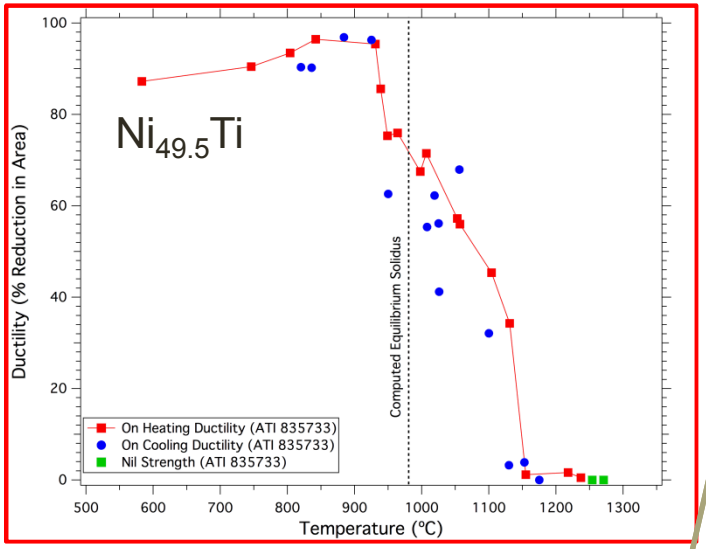


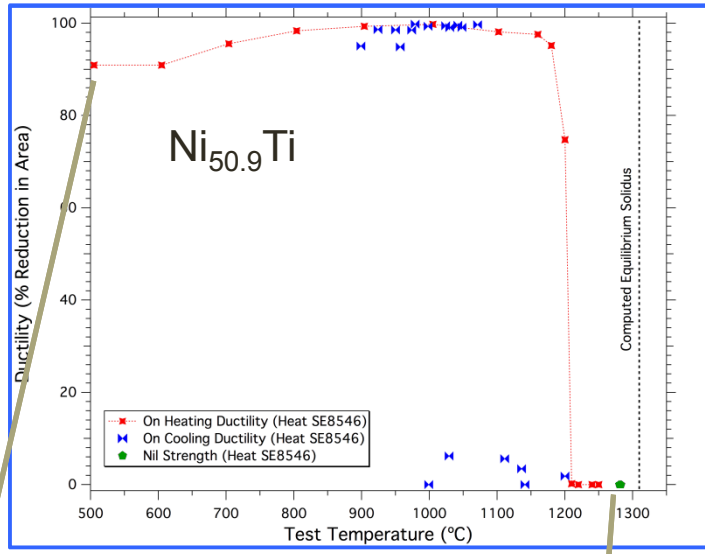


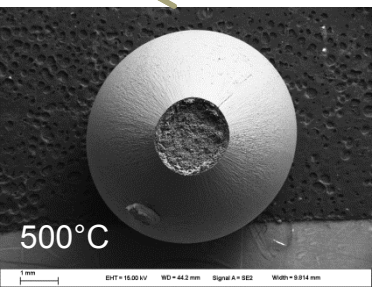
Hot Ductility Measurements Give Insight into SMA Weld Heat Affected Zone Crack Susceptibility

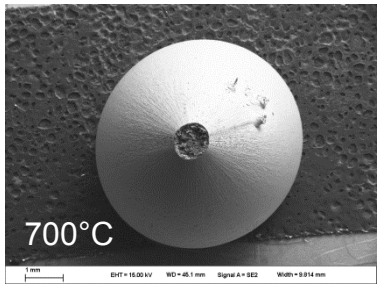
- Two SMA compositions evaluated on either side of equiatomic NiTi
- Two evaluated compositions result in unique ductility signatures

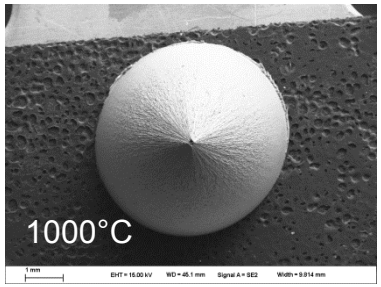


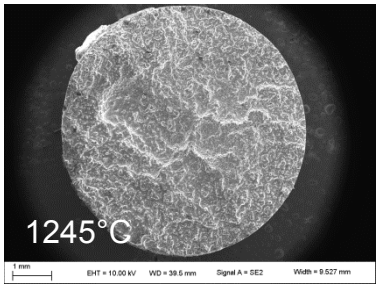


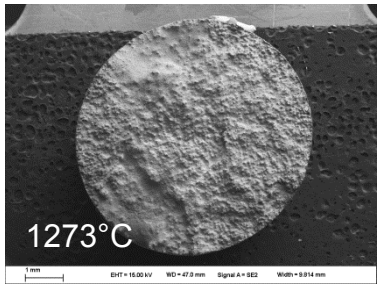








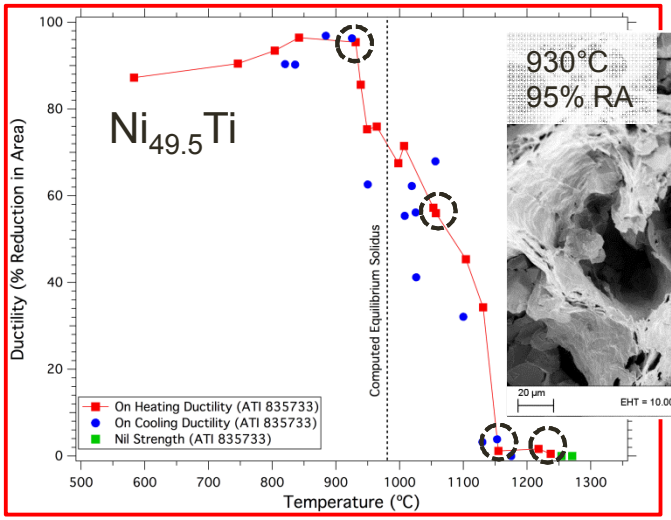


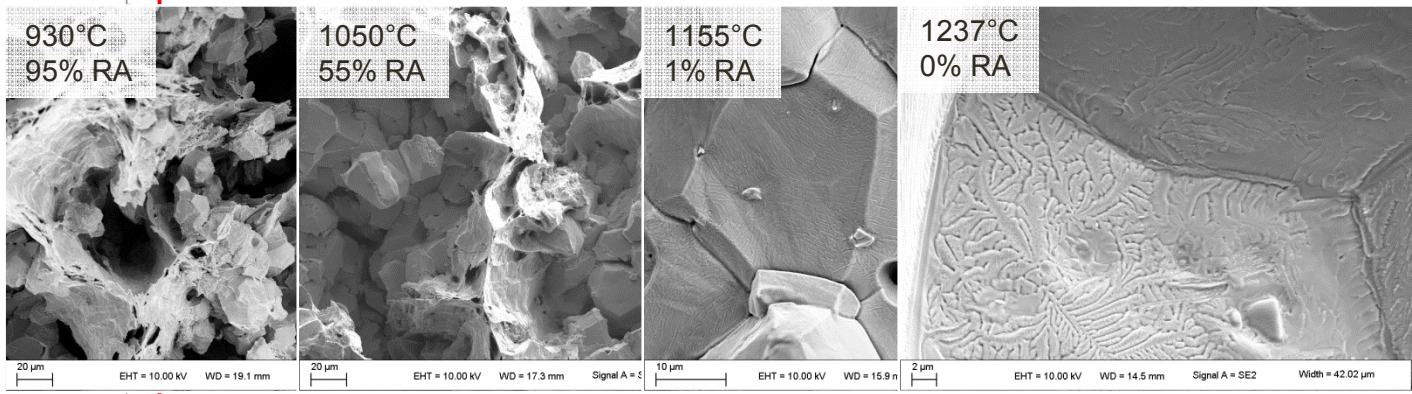


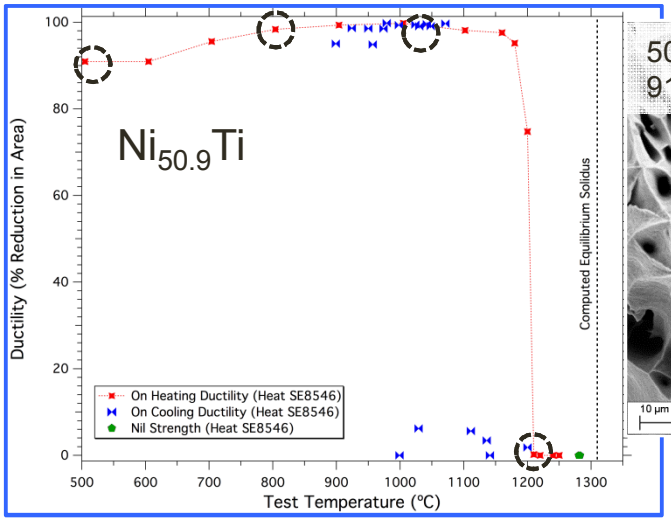
On-heating specimens for $Ni_{50.9}Ti$

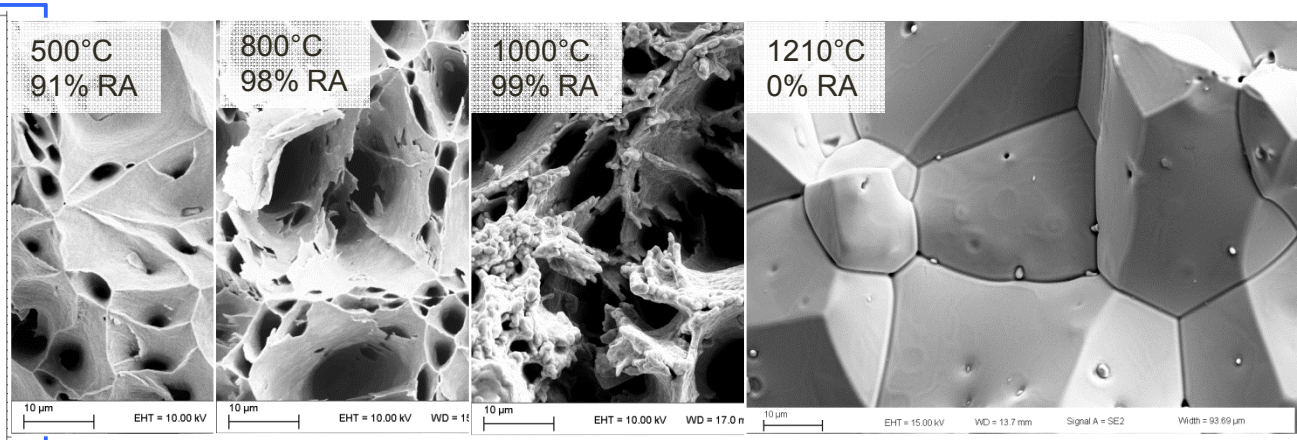
On Heating Ductility Response

- Ti-rich $Ni_{49.5}Ti$: ductility diminishes with diminishing fraction of ductile fracture features over ~200° C
- Ni-rich $Ni_{49.5}Ti$: highly ductile response on heating with abrupt loss in ductility near 1200° C



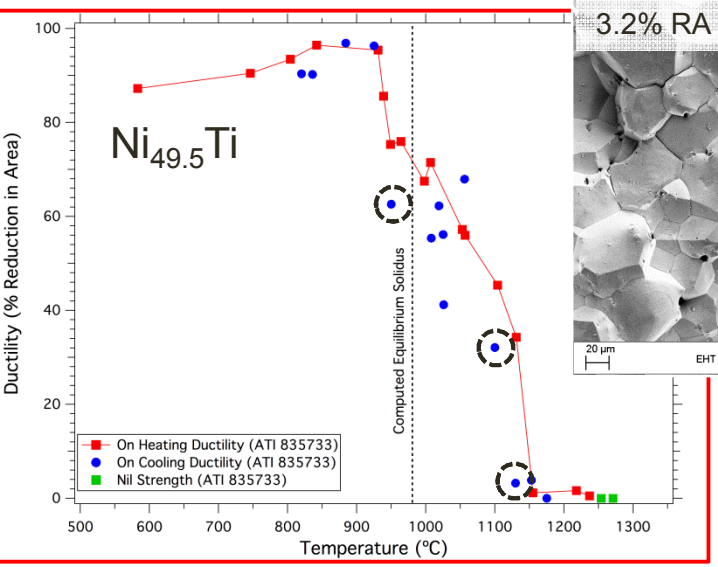


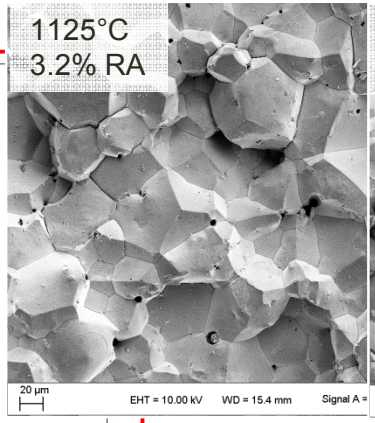


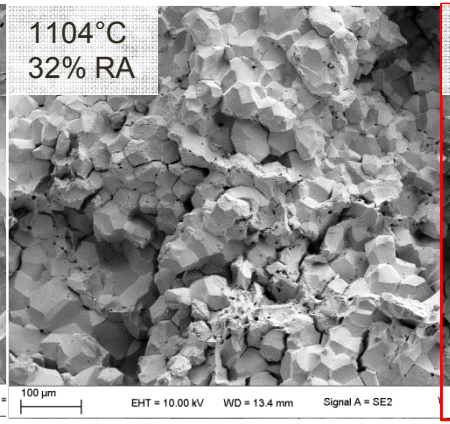


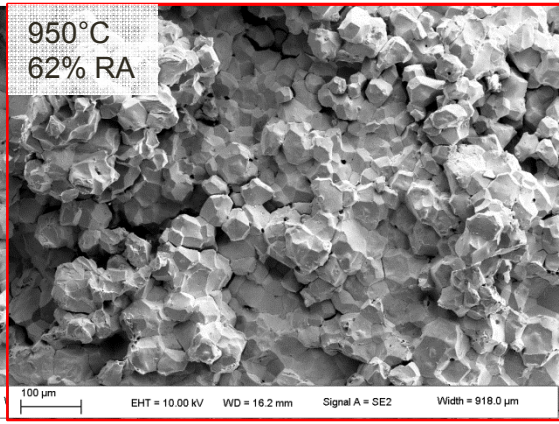
Ti-rich $Ni_{49.5}Ti$: On Cooling Ductility Response

- On cooling ductility response exhibits similar behavior to on-heating specimens
- Mixed mode fracture observed for samples tested above ~950° C

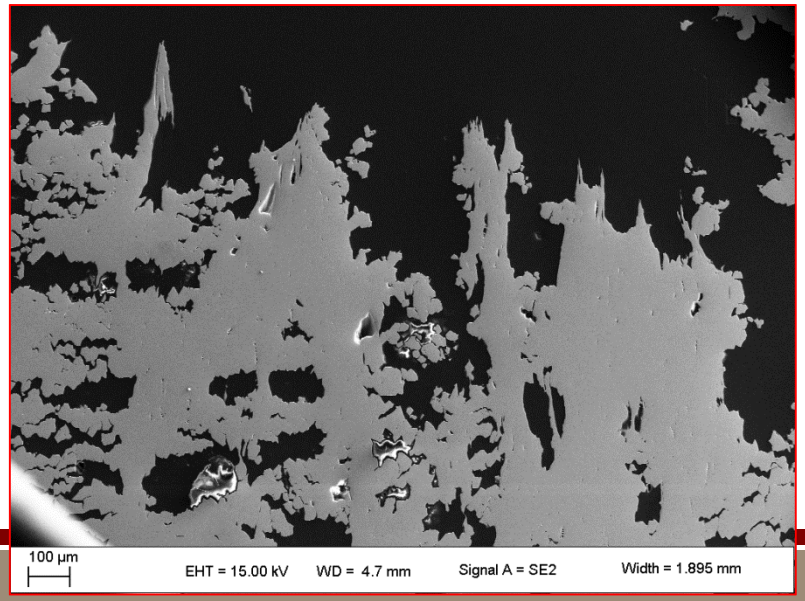






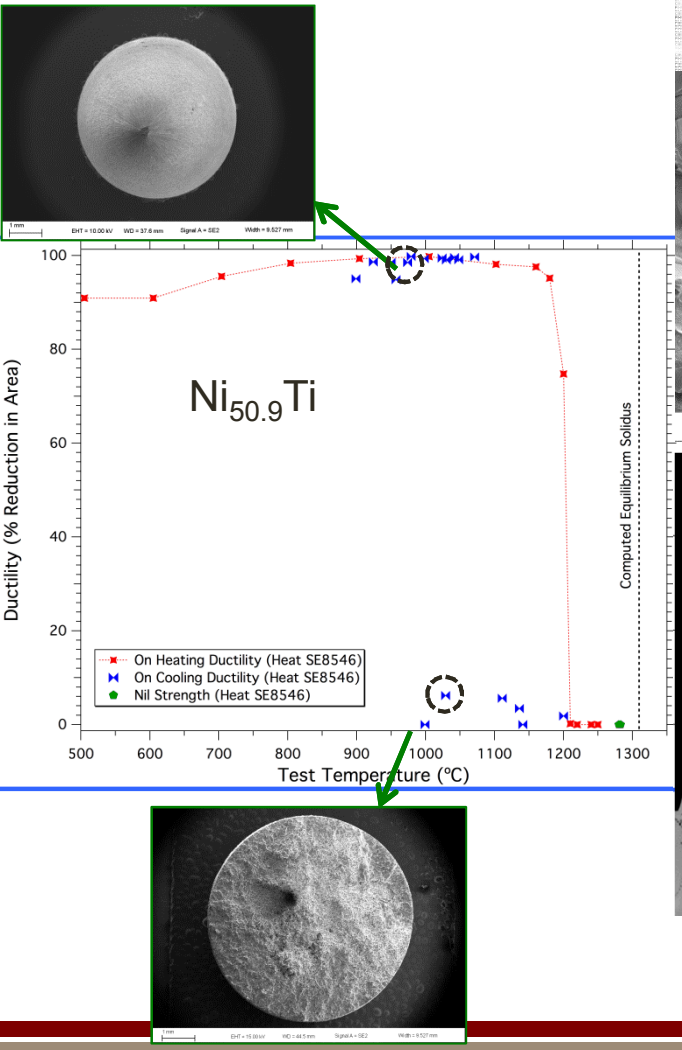


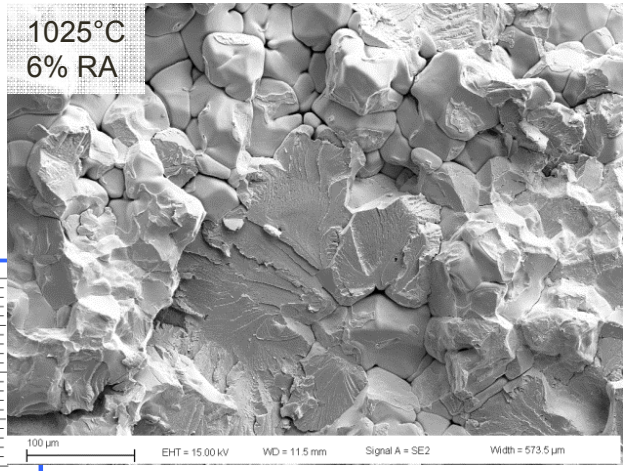
On cooling cycle peak T=1240°C

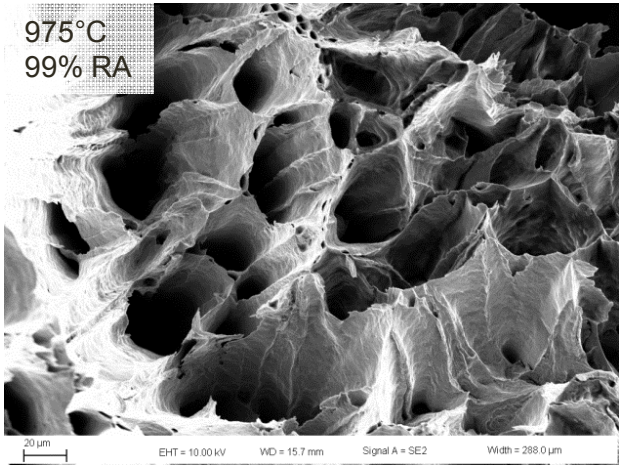


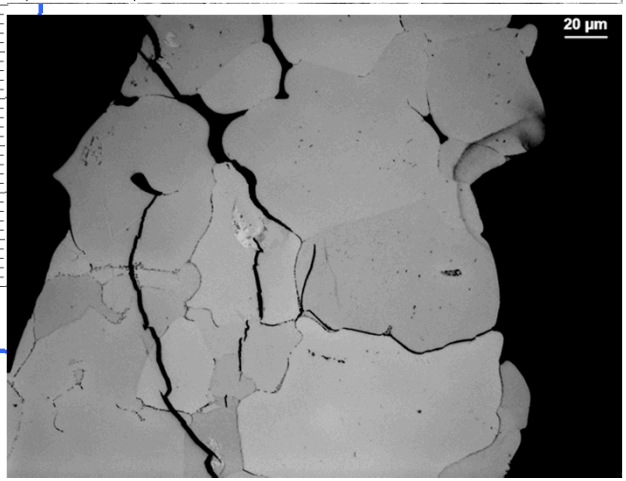
Ni-rich $Ni_{50.9}Ti$: On Cooling Ductility Response

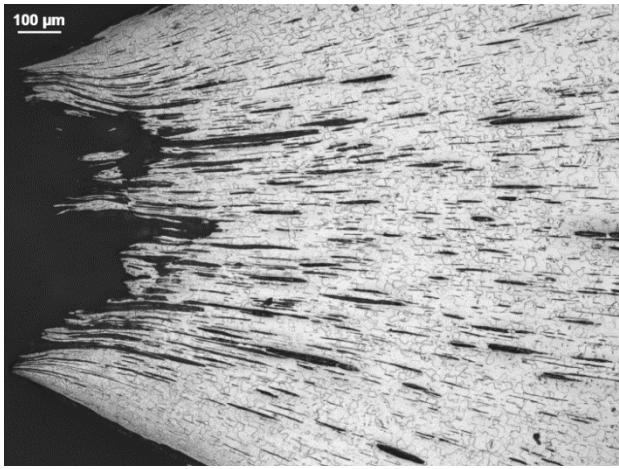
- Unique mixed mode high temperature fracture behavior on cooling
  - Observed variability in ductile response within same temperature range







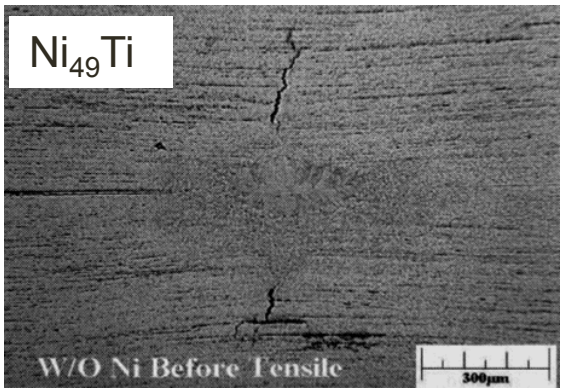




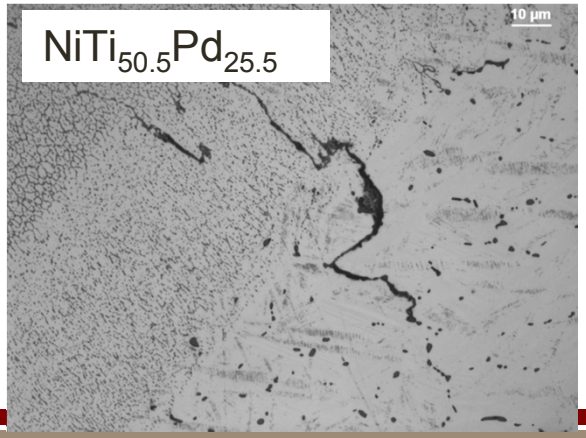
On cooling cycle peak T=1255°C

Further Analysis Required to Understand SMA High-T Fracture Behavior

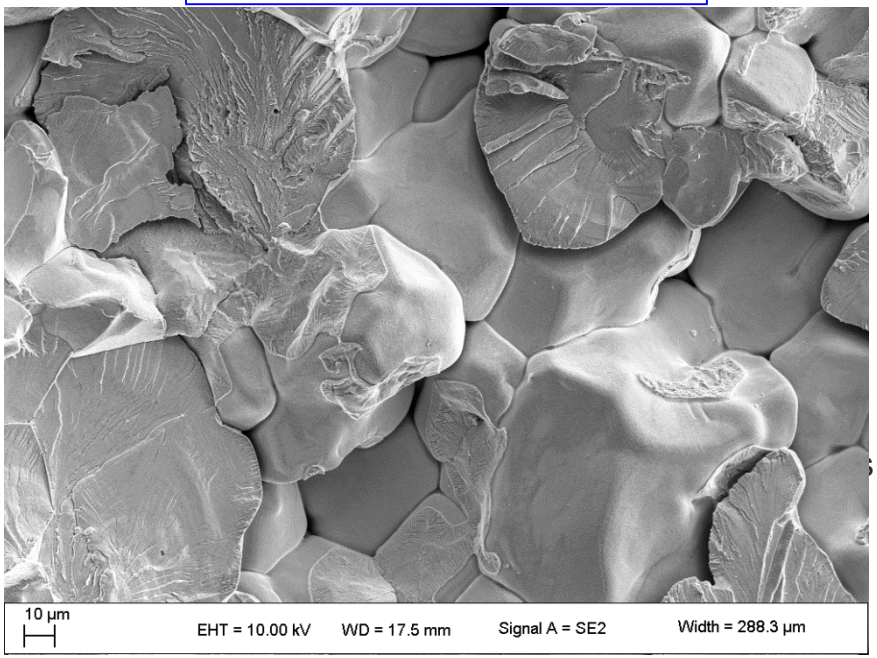
- Ductility response of Ti-rich NiTi SMA suggests greater HAZ crack susceptibility relative to Ni-rich
- Ni-rich on-cooling specimens demonstrate unusual fracture mode not generally observed in conventional engineering alloys
  - Further analysis required to identify mechanism
- Further analysis with complimentary HAZ weldability test



HAZ Cracks in Ti-rich NiTi RSW



$Ni_{50.9}Ti$
1000ºC On Cooling; ~0% RA

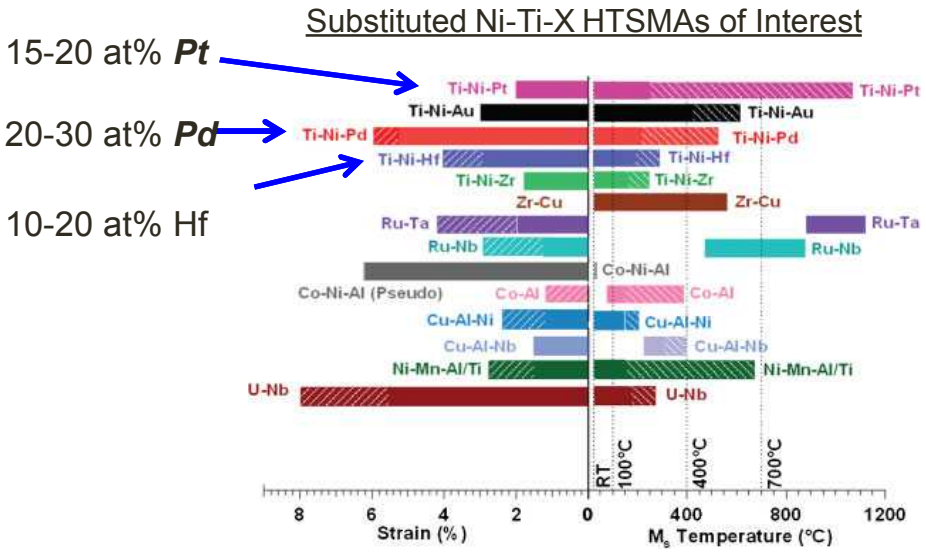


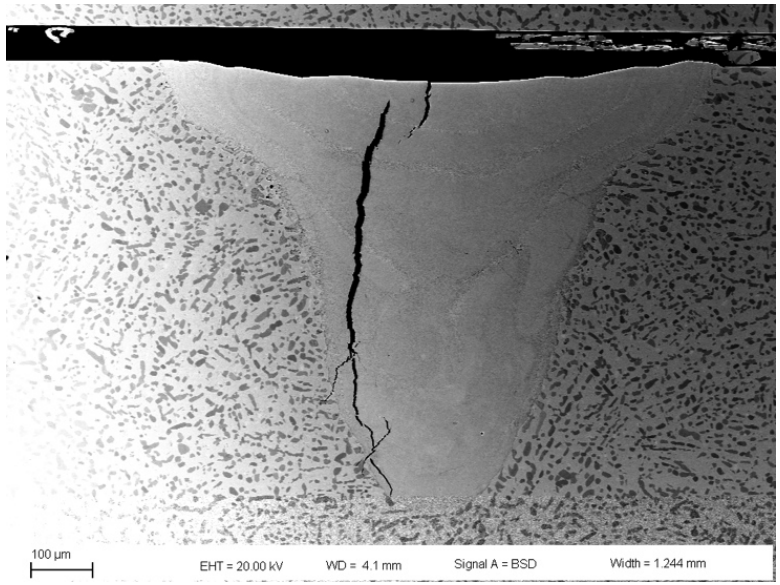
Cleavage fracture features coexist with smooth intergranular failure

M. I. Khan, "Pulsed Nd:YAG Laser Processing of Nitinol," pp. 115. in Mechanical Engineering, Vol. Doctor of Philosophy. University of Waterloo, Waterloo, Ontario, Canada, 2011.

#2 SMA Solidification Crack Susceptibility

- Cost and manufacturability issues for SMA/HTSMA preclude the use of conventional solidification crack susceptibility evaluation techniques (e.g., Varestraint)



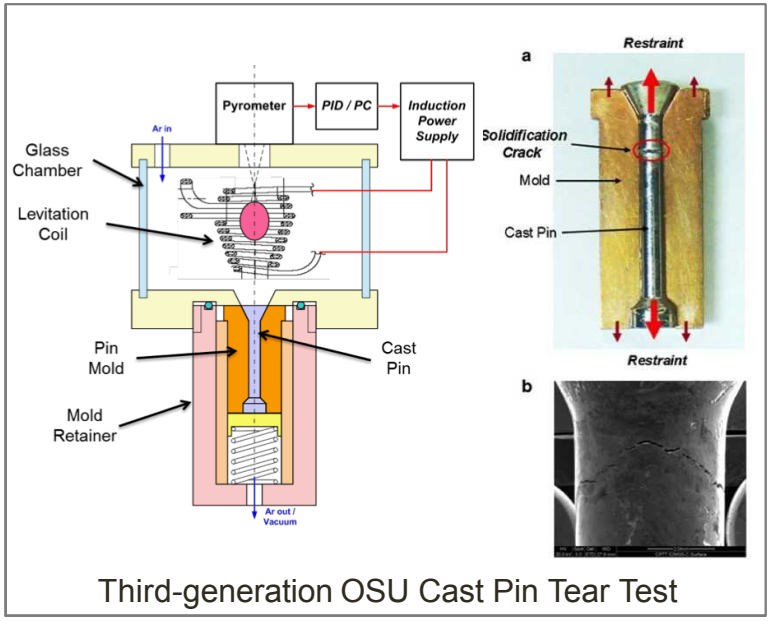


Solidification crack in Ni-Ti-Pt HTSMA laser weld

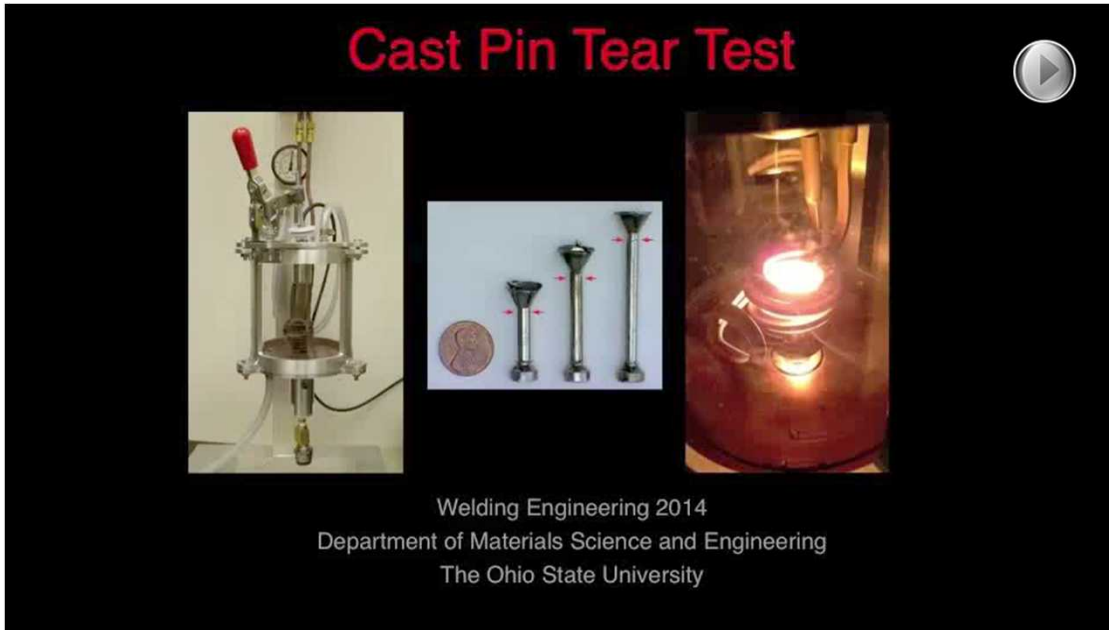
- Raw material costs for NiTiPt HTSMAs in excess of $10,000 USD/lb!

Small Volume Weldability Test Technique Enables Evaluation of SMA Solidification Cracking Susceptibility

- Cast pin tear testing (CPTT) only requires small amount of material: 10-15 g per test sample
- Good qualitative agreement with established augmented strain test methods, e.g., Varestraint

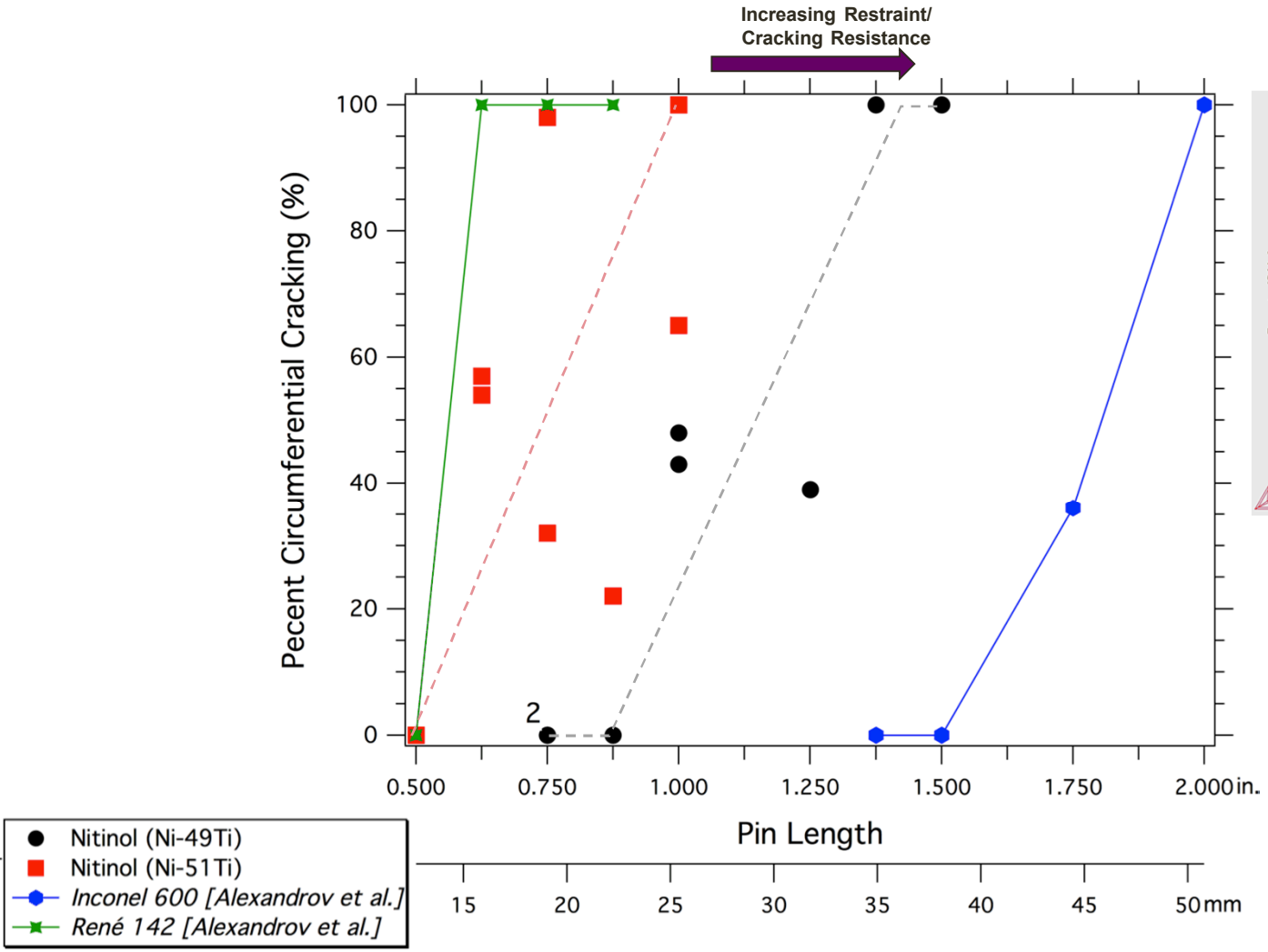


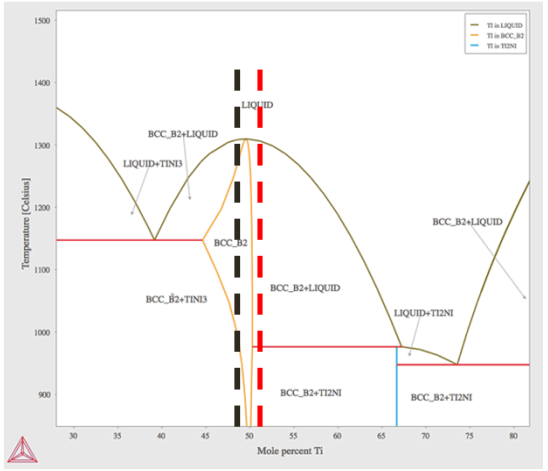
Third-generation OSU Cast Pin Tear Test



Binary Ni-Ti CPTT Results

- NiTi SMAs in general are moderately crack susceptible
  - Ti-rich SMA alloys comparatively more solidification crack sensitive compared to Ni-rich

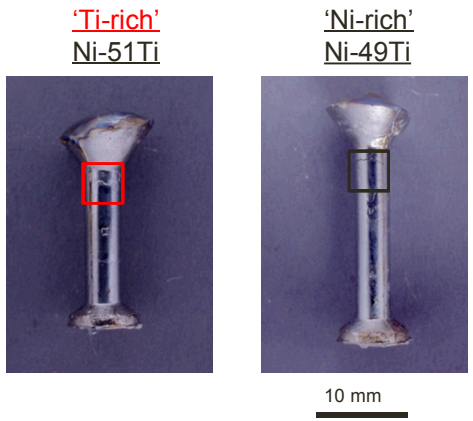


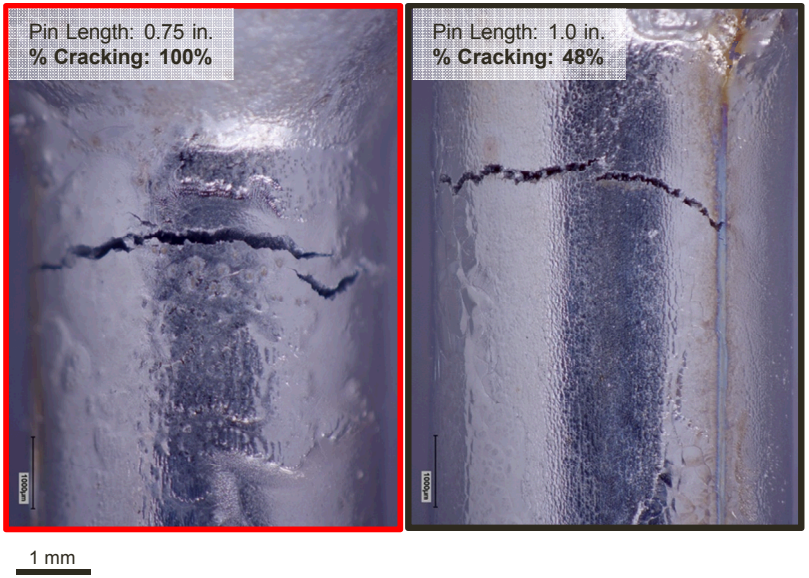


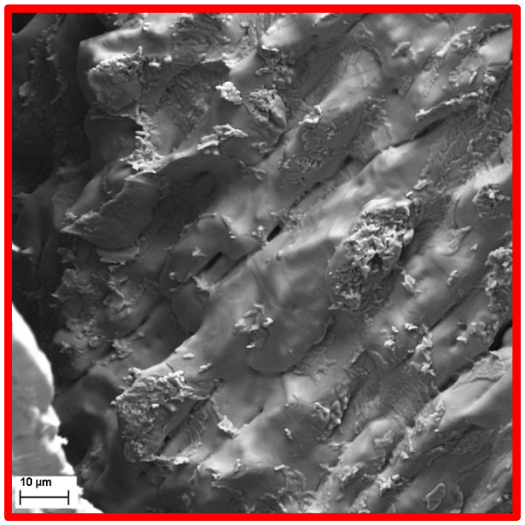
- Non-equilibrium (Scheil) solidification temperature ranges:
  - 161ºC (Ni-49Ti)
  - 335ºC (Ni-51Ti)

CPTT Fractography

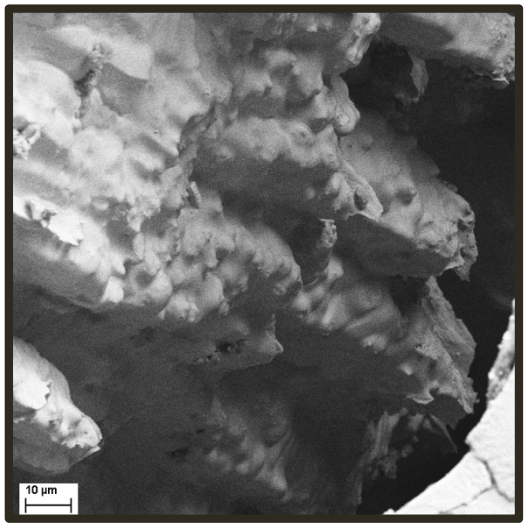
- Solidification features on CPTT fracture surface consistent with solidification cracking



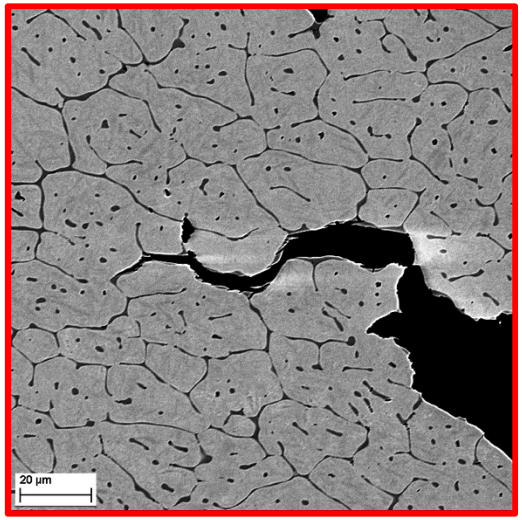




Terminal eutectic phase decorates fracture surface of Ni-51Ti CPTT



Fracture surface of Ni-49Ti largely free of terminal microconstituent on fracture surface

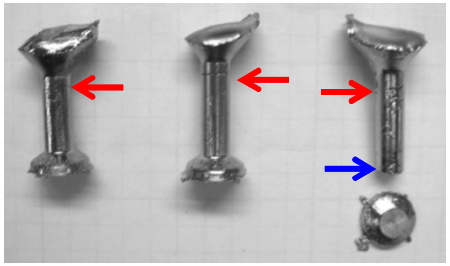


Cross section of Ni-51Ti CPTT reveals fracture along NiTi-Ti_2Ni eutectic

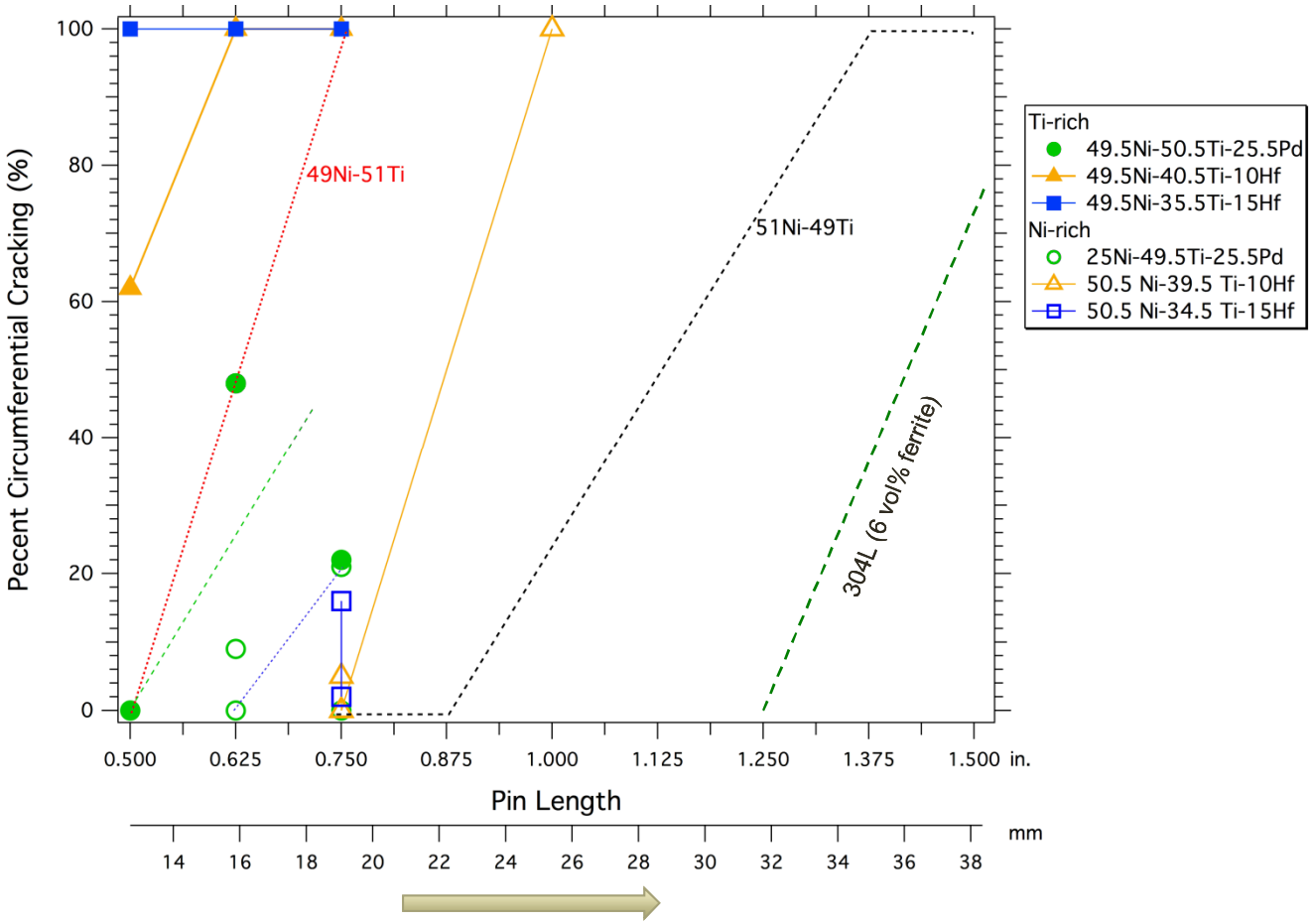
Cast Pin Tear Testing Enables Assessment of Weld Solidification Cracking Behavior for HTSMAs

- Results show HTSMA alloys have increased cracking susceptibility relative to binary Ni-Ti SMA
- Ti-rich compositions are more cracking susceptible compared to Ni-Rich

Ni-40.5Ti-10Hf



Solidification crack
Solid-state fracture

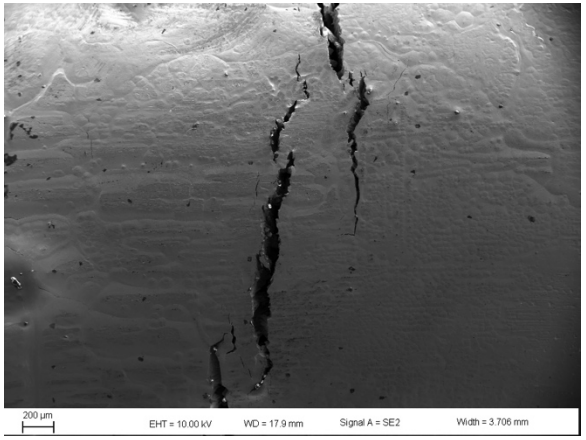


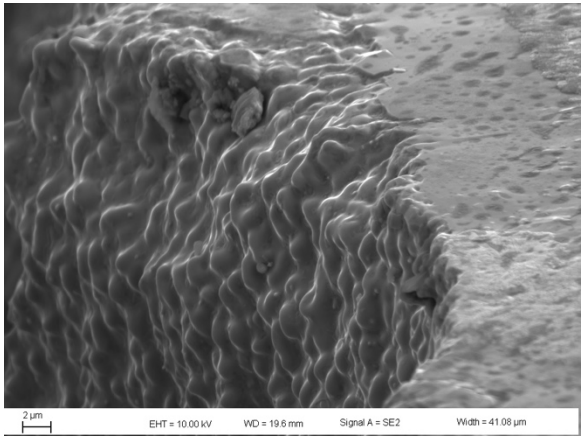
Increasing Restraint/Cracking Resistance

Solidification Crack Morphology for Ni-Ti-X HTSMAs

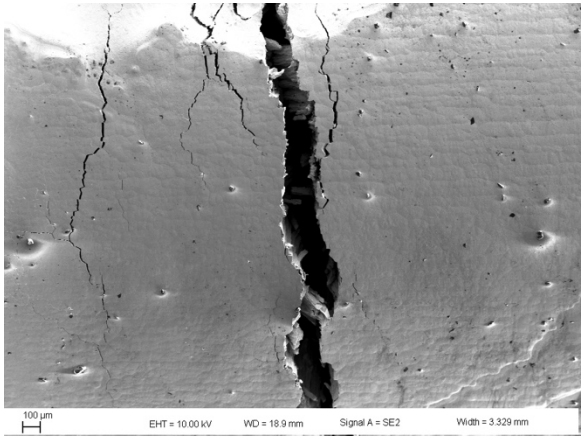
- Clear evidence of liquid present on CPTT pin fracture surfaces

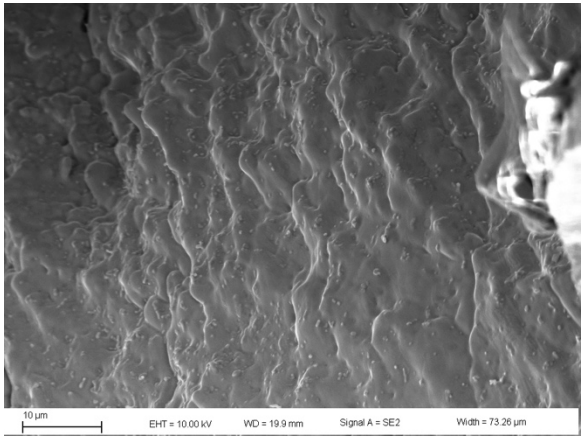
Ti-rich Ni-Ti-Hf: **10Hf** – 100% cracking – 0.500” pin length



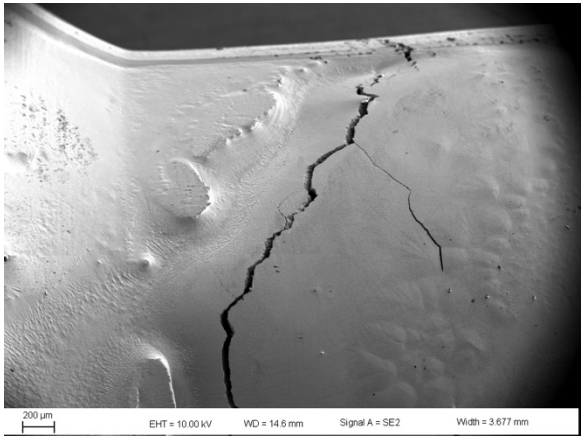


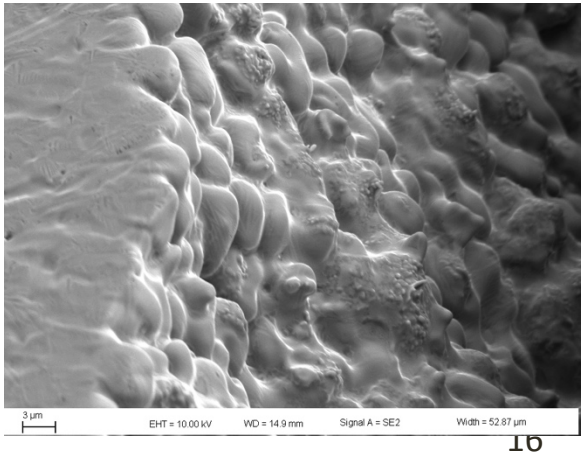
Ti-rich Ni-Ti-Hf: **15Hf** – 100% cracking – 0.750” pin length





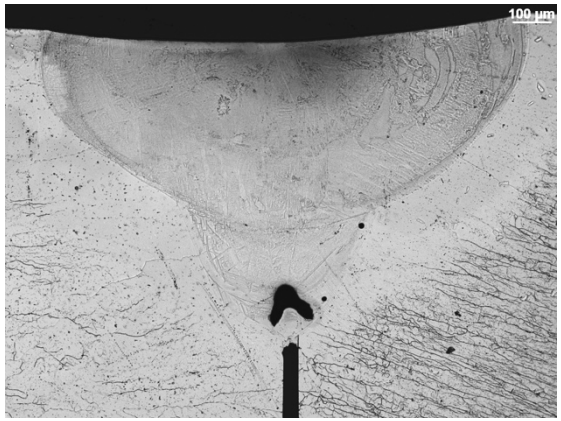
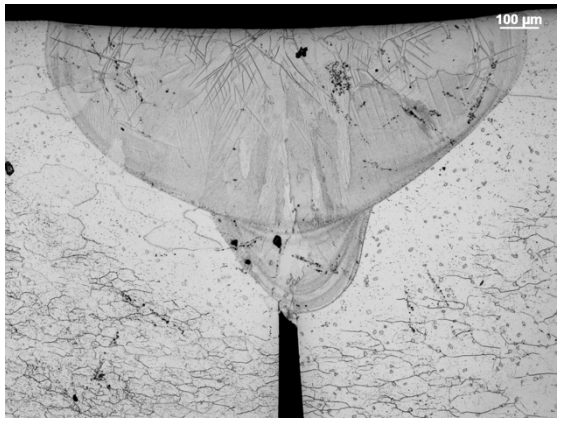
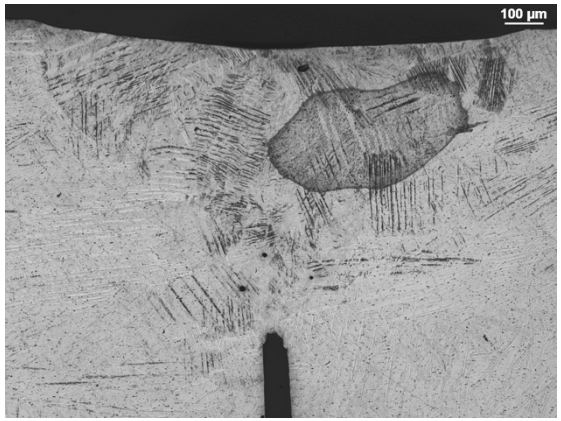
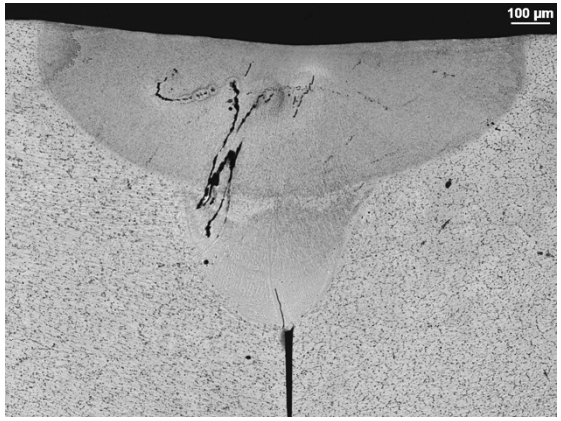
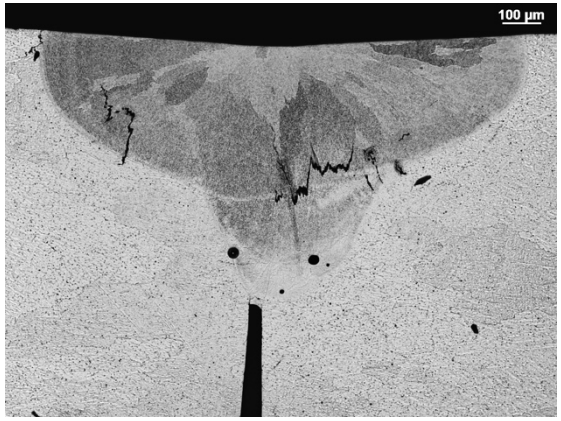
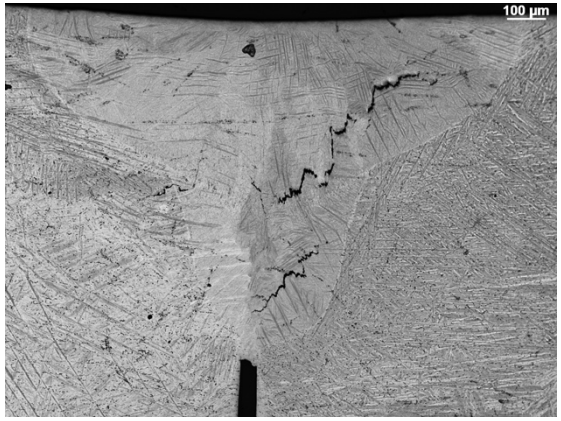
Ti-rich Ni-Ti-Hf: **25.5Pd** – 100% cracking – 0.625” pin length





Laser Welding of Ti-rich HTMSAs Problematic in Practice

- Cast Pin Tear Testing suggests Ni-rich HTSMA alloy compositions have increased weld solidification crack resistance compared to Ti-rich. Behavior demonstrated in continuous-wave laser welds

	$Ni_XTi_{(100-X)-15}Hf_{15}$	$Ni_XTi_{(100-X)-10}Hf_{10}$	$Ni_{X-25.5}Ti_{100-X}Pd_{25.5}$
Ni-rich, X=50.5			
Ti-rich, X=49.5			

All laser welds produced using same welding parameters: 500W, 1.33 in./sec. travel speed

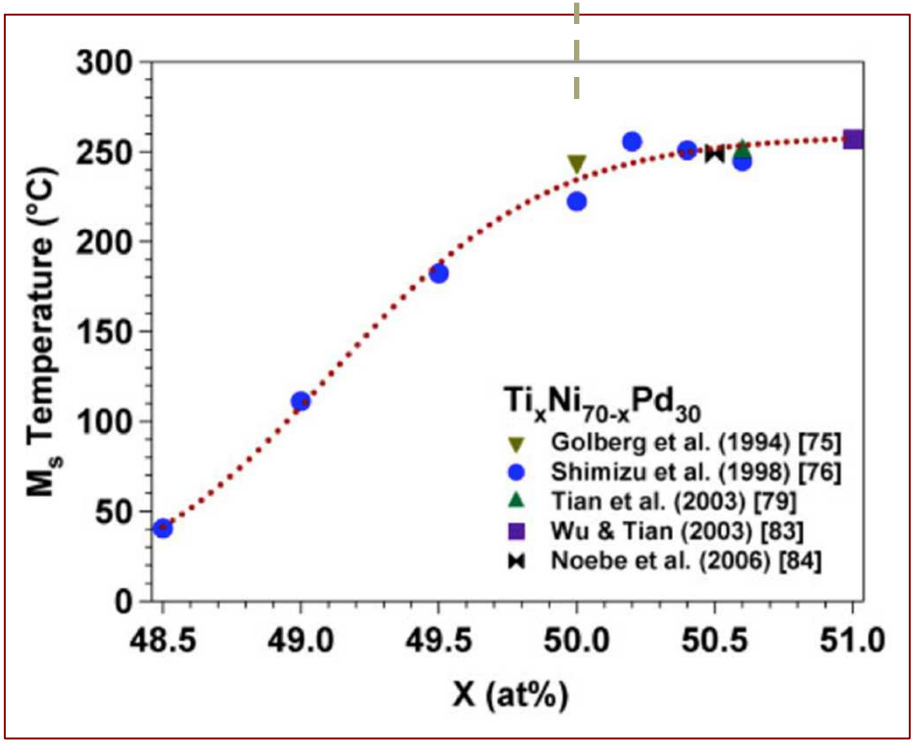
HTSMA Practical Implications

- Ti-rich ternary Ni-Ti-X HTSMAs ideal for compositional robustness with respect to transformation temperature may not be ideal selection for fusion welding applications

- Ni filler metal may be practical means to mitigate solidification cracking

Ni-rich
Highly composition-dependent transformation temperature

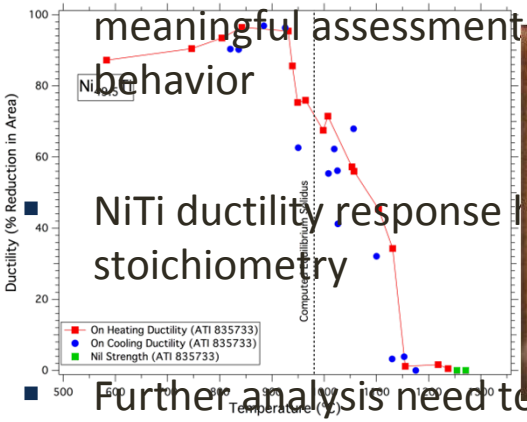
Ti-rich
Composition-independent transformation temperature

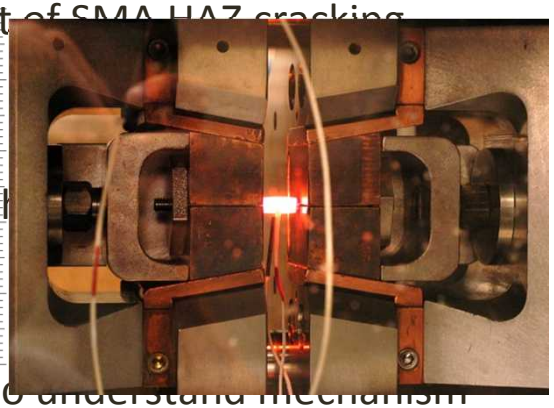


*Internal SNL Report: Susan, DF, et. al. SAND2014-0105. 2014

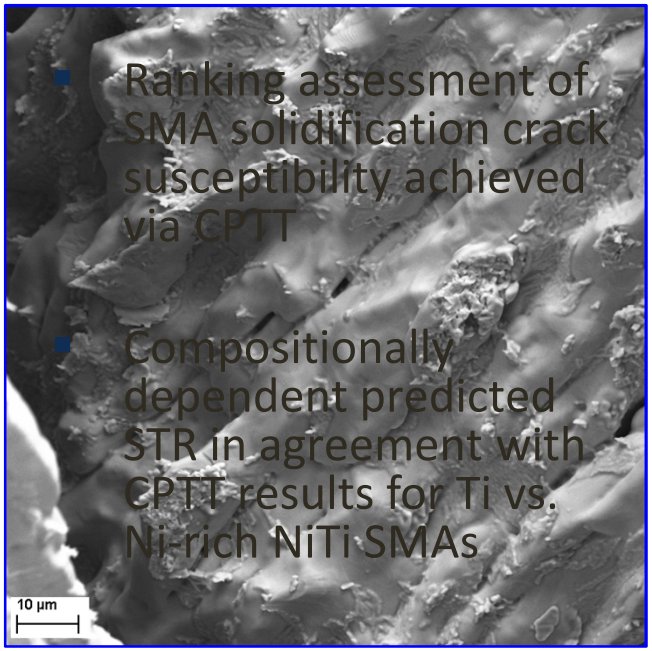
Concluding Remarks

- Gleeble hot ductility experiments provide basis for meaningful assessment of SMA HAZ cracking behavior
- NiTi ductility response h… stoichiometry
- Further analysis need to understand mechanism for unusual high temperature cleavage fracture

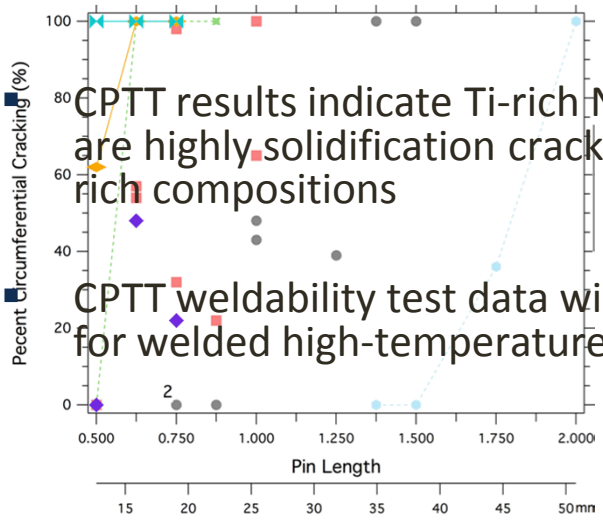


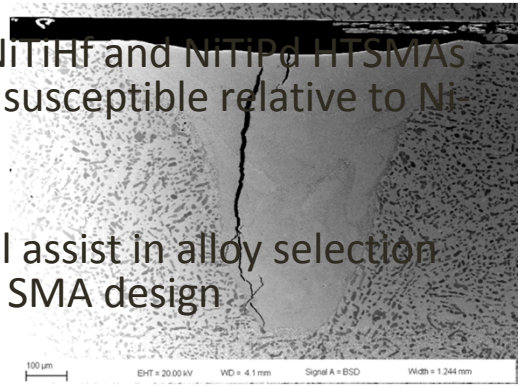


- Ranking assessment of SMA solidification crack susceptibility achieved via CPTT
- Compositionally dependent predicted STR in agreement with CPTT results for Ti vs. Ni-rich NiTi SMAs



- CPTT results indicate Ti-rich NiTiHf and NiTiPd HTSMAs are highly solidification crack susceptible relative to Ni-rich compositions
- CPTT weldability test data will assist in alloy selection for welded high-temperature SMA design





Acknowledgments

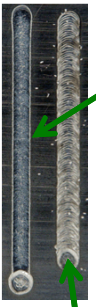
- The work has been funded wholly by SNL Laboratory Directed Research & Development (LDRD)

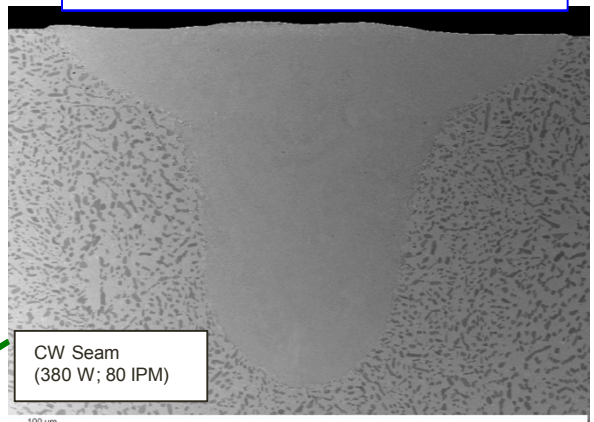
- Special thanks to:
  - The Ohio State University: Welding & Joining Metallurgy Group
    - Tyler Payton, Matt Duffey, Nicole Brown, Ken Copley,
  - Peter Duran
  - Don Susan
  - Charlie Robino
  - Alice Kilgo
  - Bonnie McKenzie
  - Amy Allen

HTSMA Laser Beam Weld

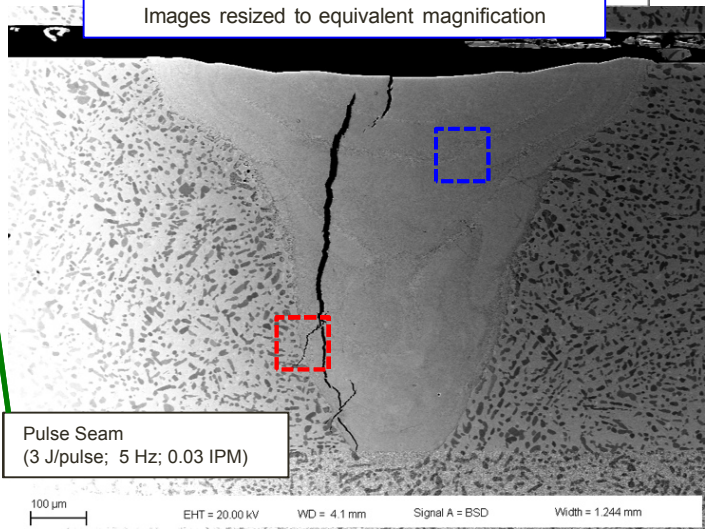
- Autogenous laser welds can be successfully be made on cast Ni-Ti-Pt HTSMAs
- Cracking in pulsed laser welds highlights material process sensitivity

HTSMA: 31.5Ni-50.5Ti-18Pt

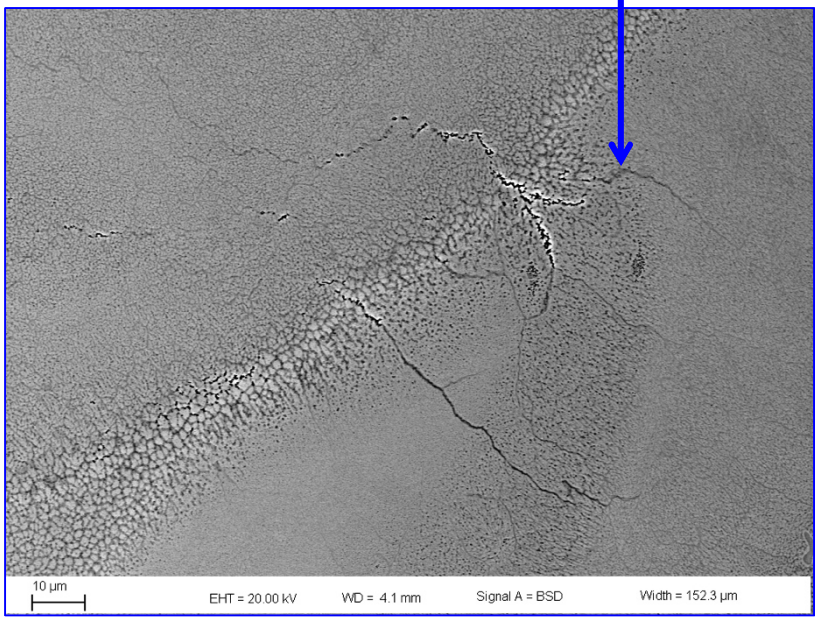


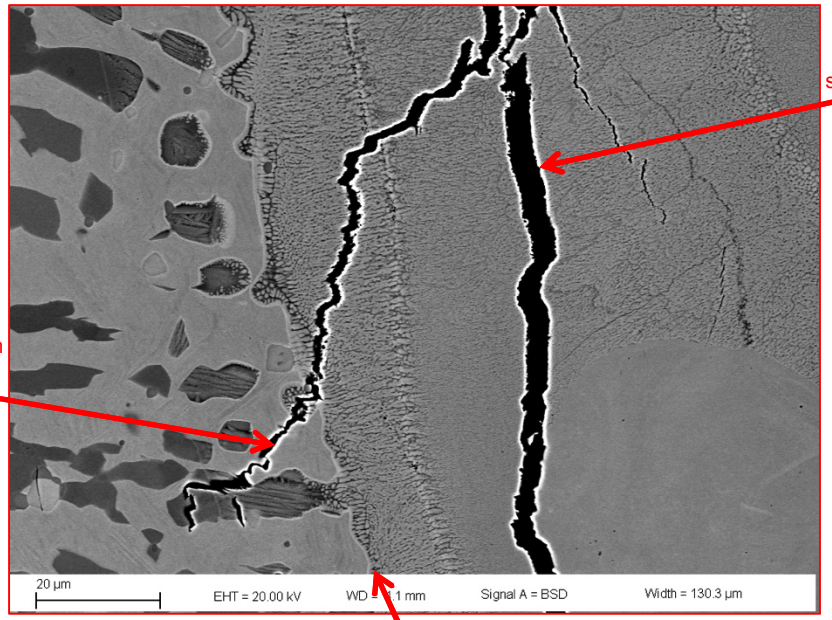


Images resized to equivalent magnification



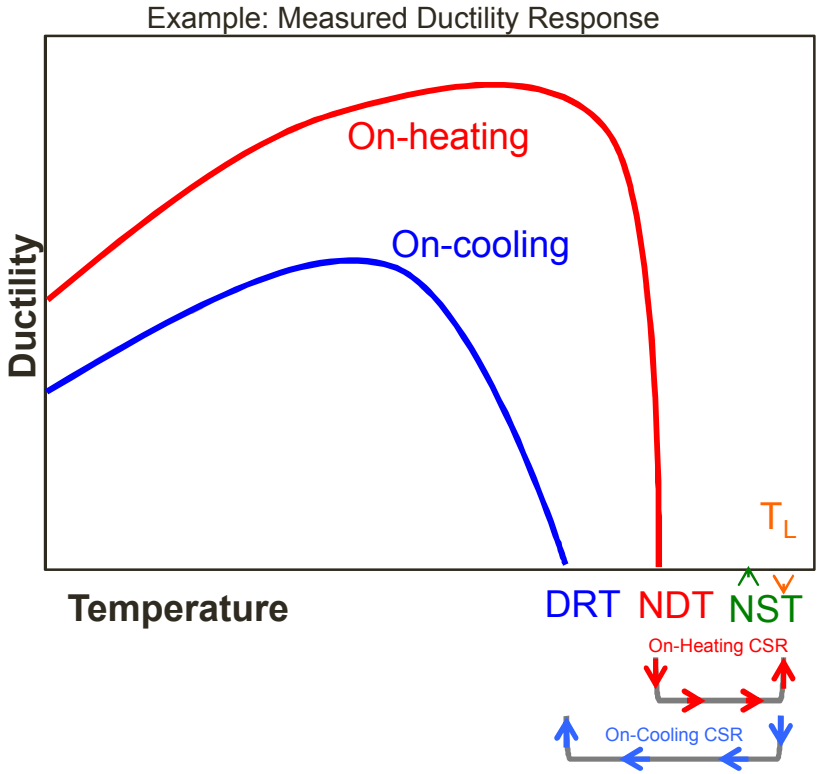
Liquid backfilling of solidification crack along pulse boundary

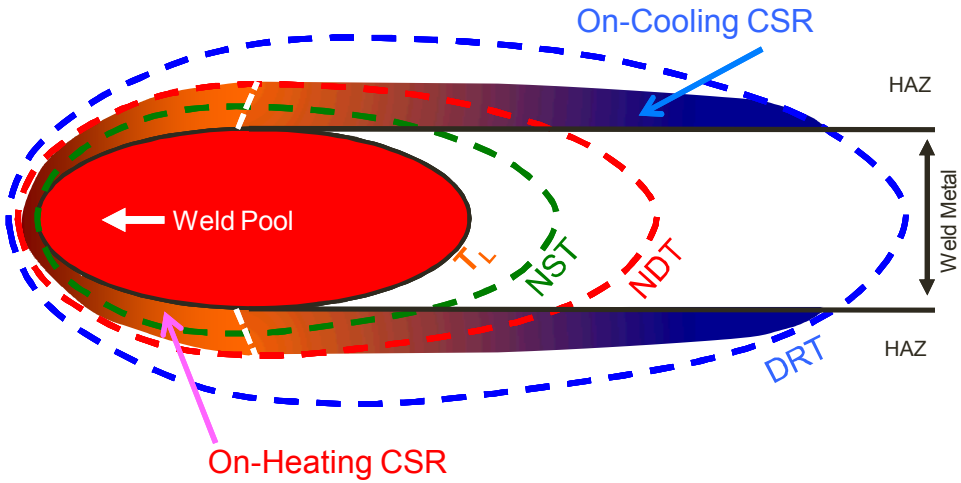




Understanding SMA Heat Affected Zone (HAZ) Behavior

- Material ductility is related to cracking susceptibility
- Hot ductility test (HDT) measures material ductility as a function of HAZ-relevant temperatures/heating rates



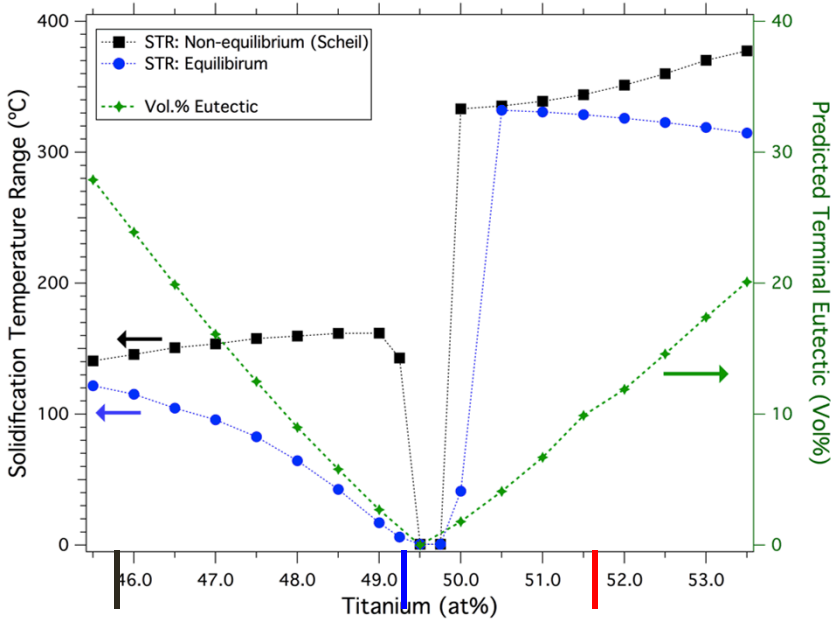


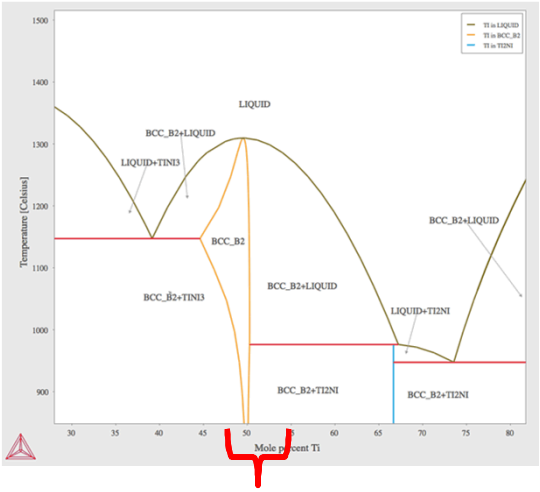
Translation of Measured HDT Temperatures to HAZ Crack Susceptible Regions (CSR)

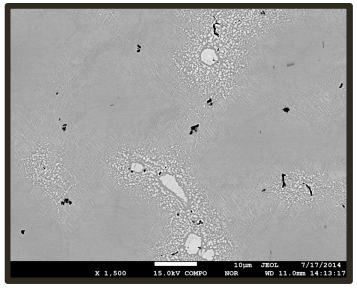
- NST: Nil-strength temperature
  - T at which material cannot support load
- NDT: Nil-ductility temperature
  - T at which material fails with no ductility
- DRT: Ductility recovery temperature
  - T at which ductility recovered on cooling

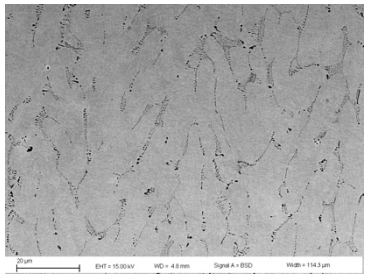
Significant Solidification Temperature Range Compositional Dependence for NiTi SMAs

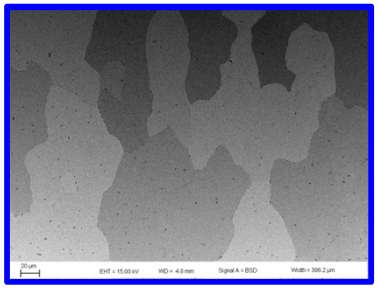
- Ti-rich alloys show large predicted solidification temperature range (STR).
  - Qualitatively agrees with preliminary CPTT tests
- Near-equiatomic and Ni-rich SMAs less prone to solidification cracking

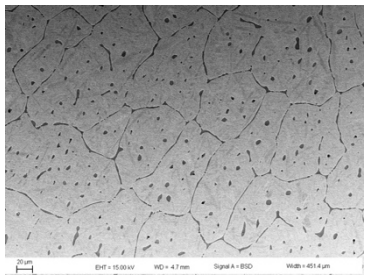


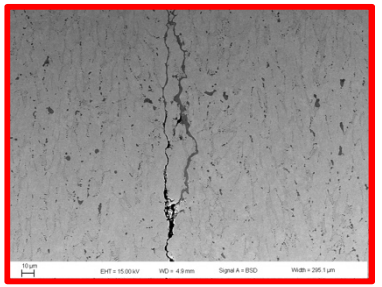












Ni-Rich

Near-equiatomic

Ti-Rich

$L \rightarrow L + B2 \rightarrow L + B2 + (B2 + TiNi_3)_{eu} \rightarrow B2 + (TiNi_3)_{eu} + Ti_3Ni_4$

$L \rightarrow L + B2 \rightarrow B2$

$L \rightarrow L + B2 \rightarrow L + B2 + (B2 + Ti_2Ni)_{eu} \rightarrow B2 + (Ti_2Ni)_{eu}$

Understanding SMA Heat Affected Zone (HAZ) Behavior: Functional Behavior

- Technique is informative regarding how joining process alters functional behavior of specific regions surrounding weld
- Simulated Ni-49.6Ti HAZ shows apparent shift in Ap with increasing HAZ peak temperature
- On-cooling SMA behavior altered as a result of HAZ thermal cycles
  - 2-stage transformation destroyed with peak HAZ temperatures 700ºC and greater