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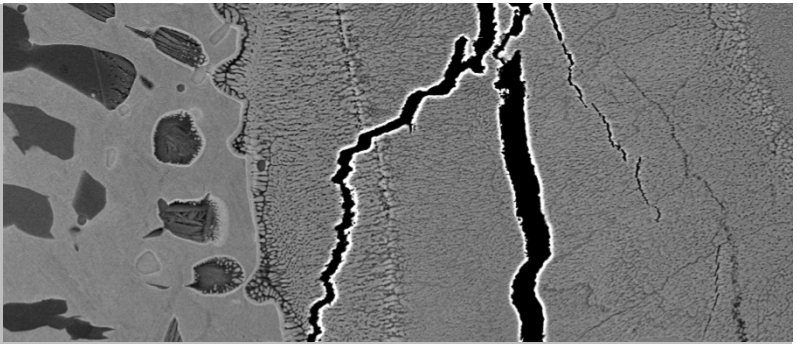
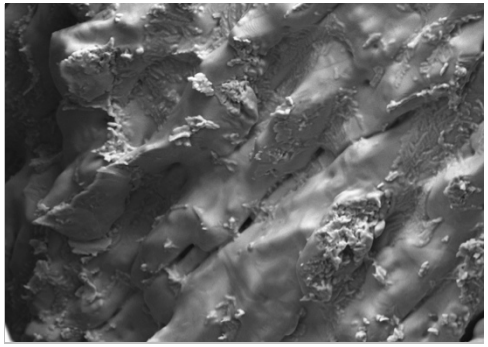
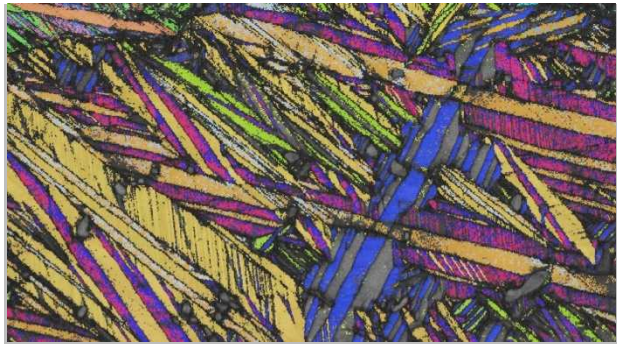

Weldability of Advanced Shape Memory Alloys

J. M. Rodelas

Sandia National Laboratories, Albuquerque NM

Materials Science & Technology 2014

Oct. 13th, 2014

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

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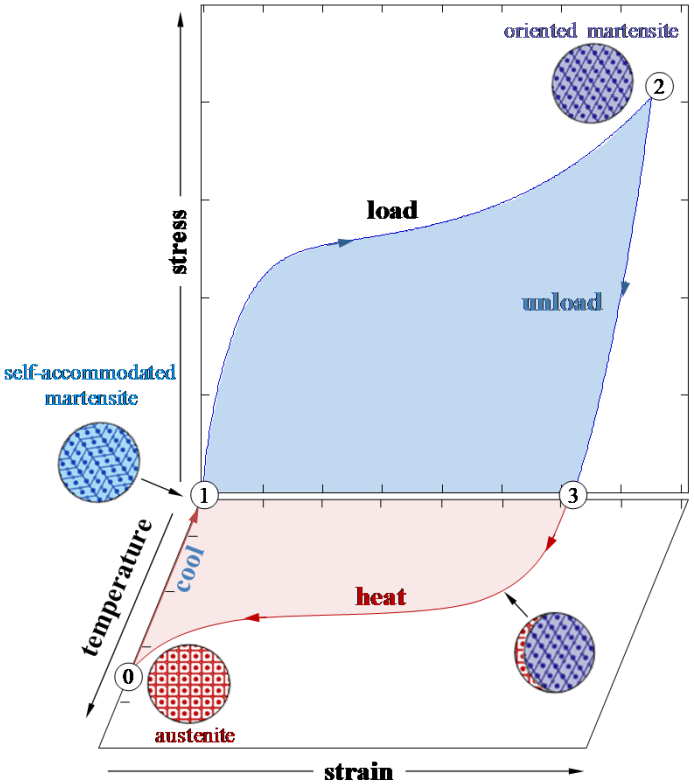
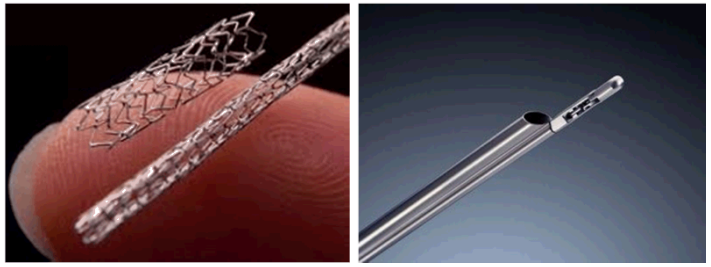
What is a Shape Memory Alloy (SMA)?

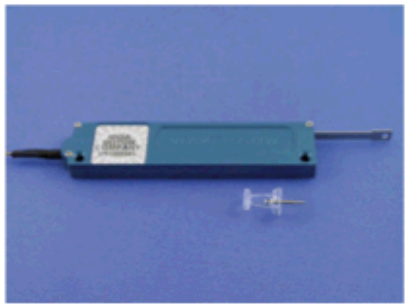
- Unique class of intermetallic alloys that changes shape using a 1st order transformation
- Widely used conventional NiTi intermetallic SMA has functional limitations of ~100ºC
- New high temperature (HT) SMAs being developed to perform >100ºC.



Biomedical Devices



(HT)SMA Compact Actuators



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

SMA anti-scald device

Image source: Bouge R. Assembly Automation. 29:3 pp214-19 (2009)

Morphing Aircraft Structures

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

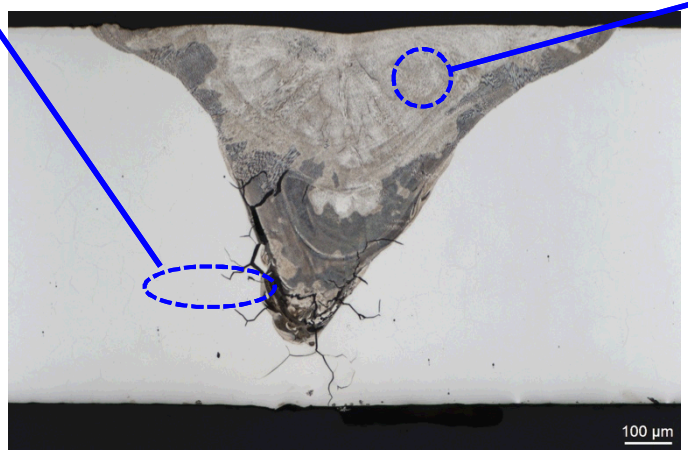
Why Explore the Weldability of Shape Memory Alloys?

- Weld metallurgical phenomena that determine material weldability has received little attention for SMAs
- Eventual development of robust welded high-temperature (HT) SMAs in real-world applications requires understanding of weld metallurgy

<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

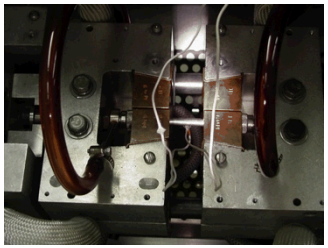
*multi-pass welds

Weldability of SMAs/HTSMAs: A Multi-Technique Approach

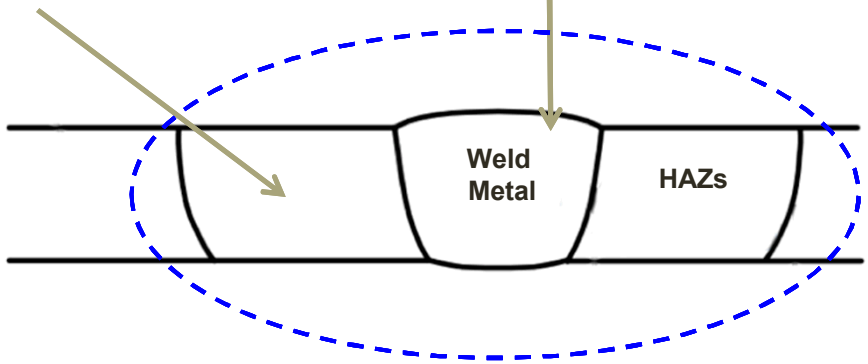
- True assessment of SMA weldability will require an understanding metallurgical behavior governing SMA cracking during welding

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

#1:
Heat Affected Zone Cracking
Evaluating elevated temperature ductility



Gleeble Thermomechanical Simulator



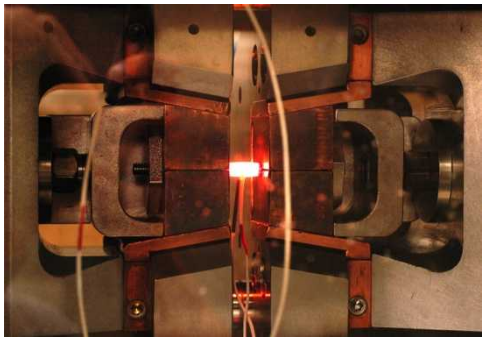
#2:
WM Solidification Cracking
Evaluating SMA/HTSMA susceptibility

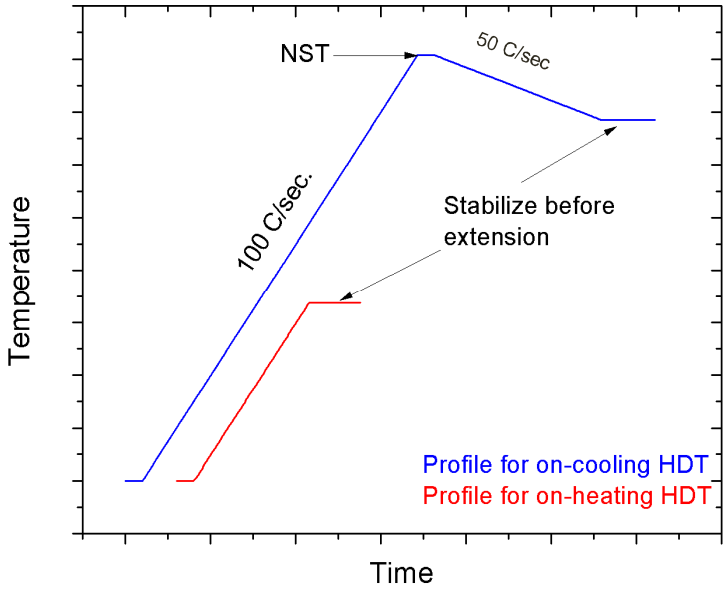
Cast Pin Tear Test Sample

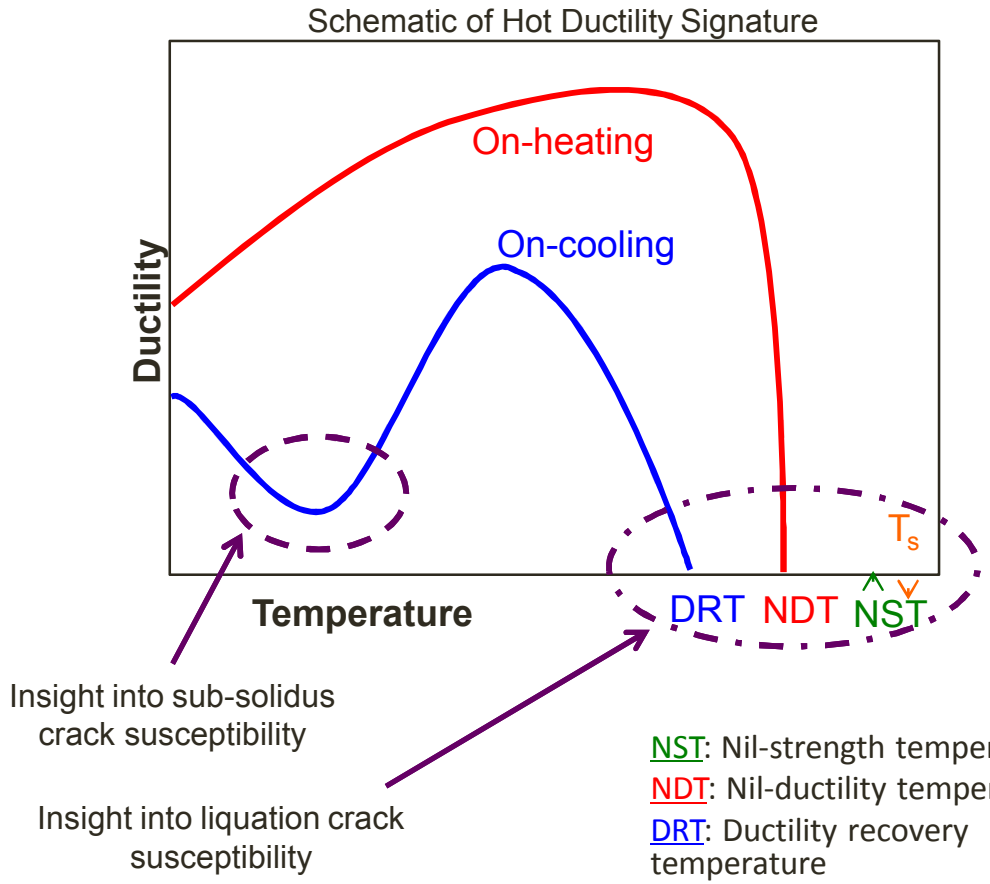
Existing SMA welding studies examine behavior of all weld zones combined

#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

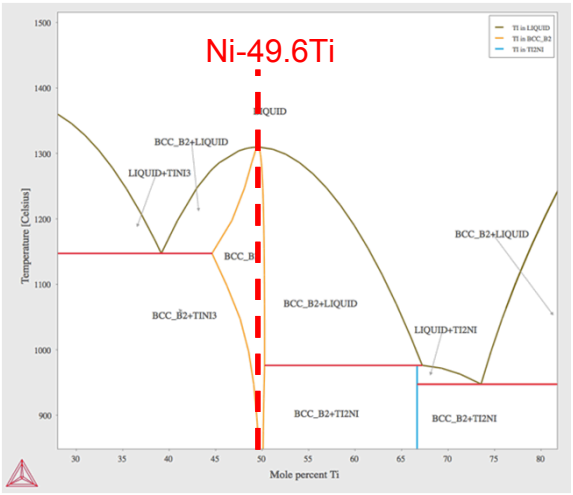




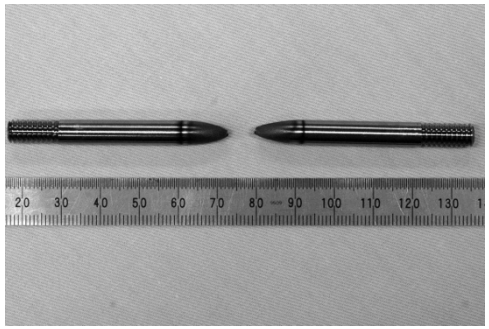


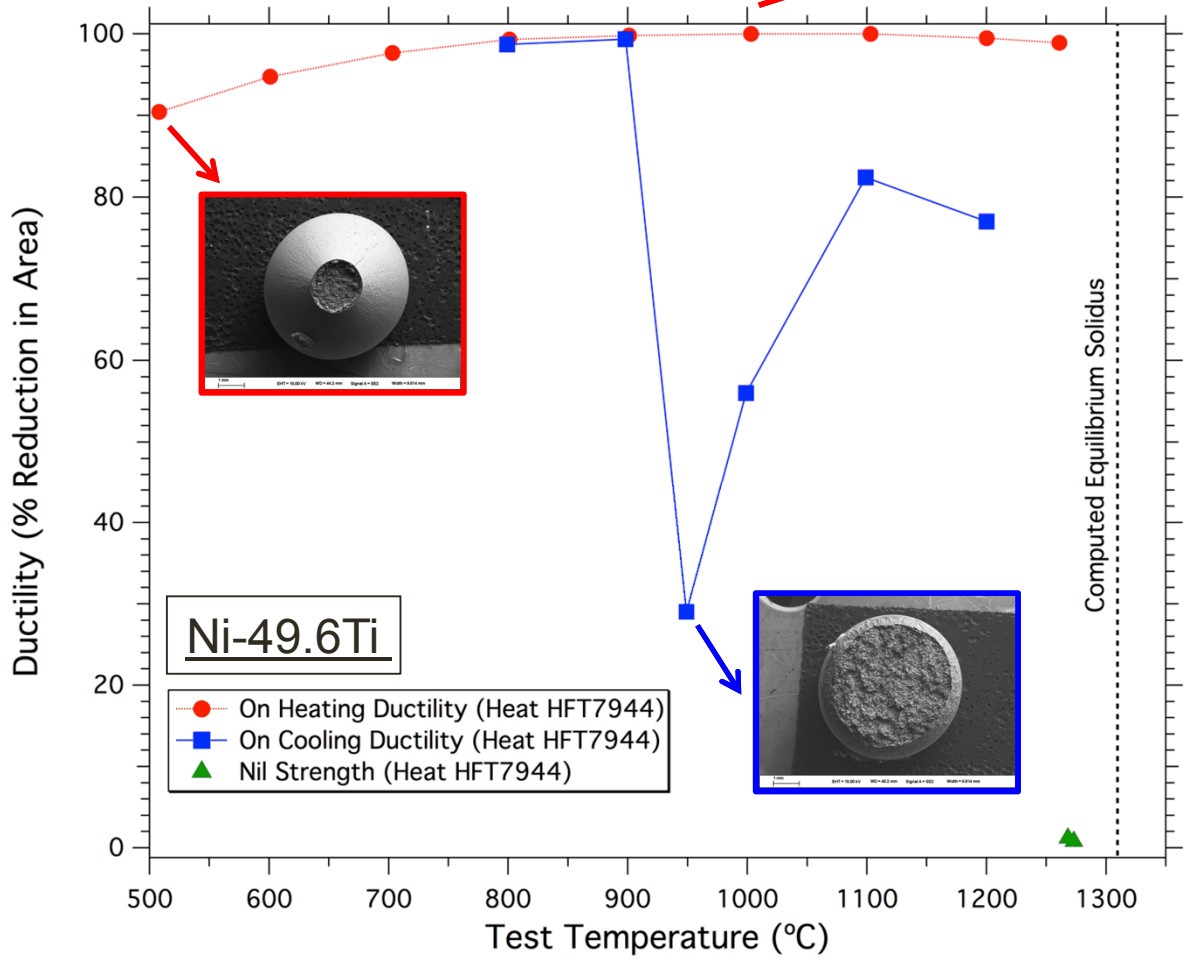
Understanding SMA Heat Affected Zone (HAZ) Behavior

- Ni-49.6Ti demonstrates negligible HAZ liquation cracking susceptibility
- Sharp drop in ductility ~950ºC on cooling



Calculated Ni-Ti Binary

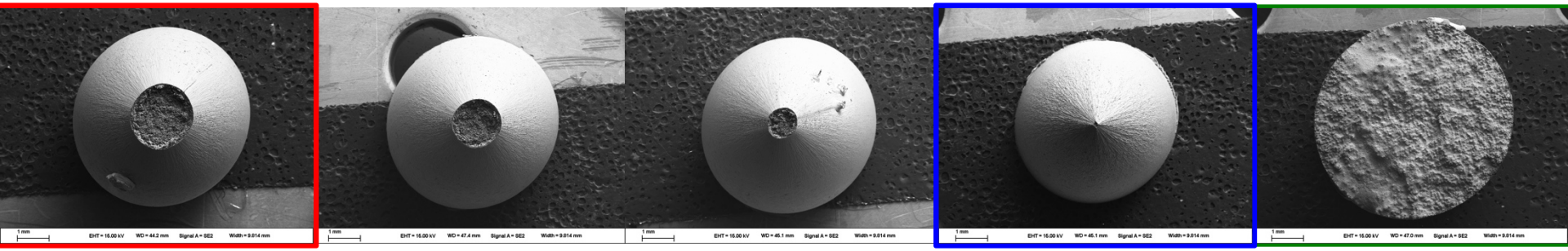


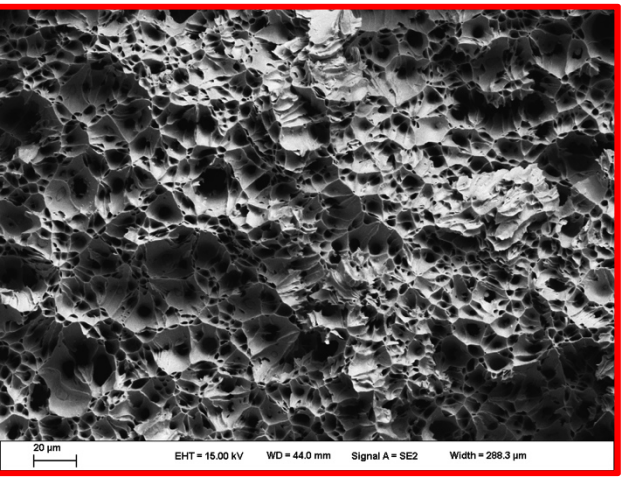


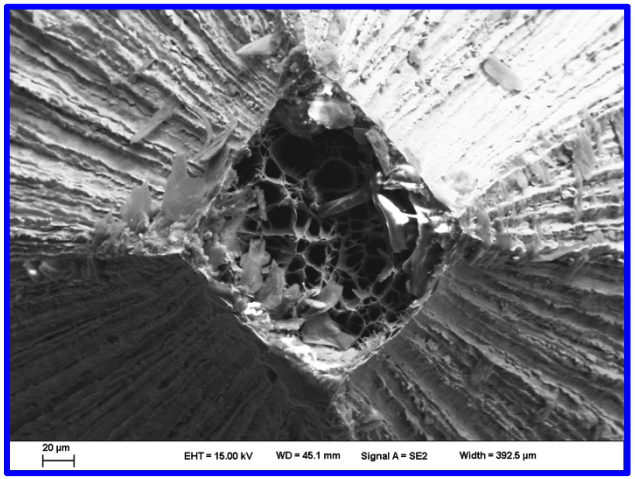
HDT Fractography: On Heating: Ni-49.6Ti

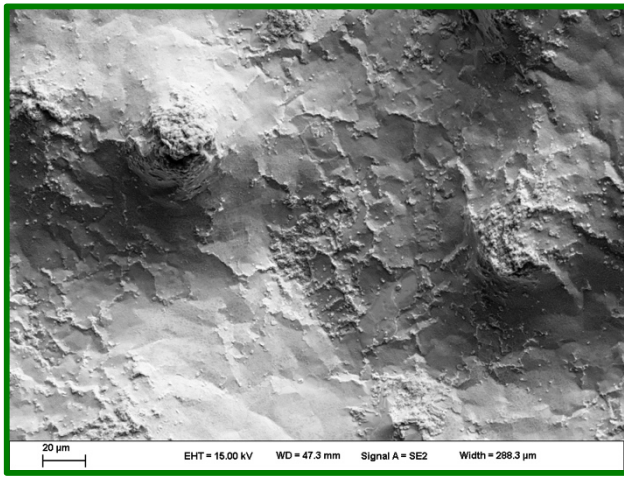
- On heating HDT samples exhibit ductile rupture up to NST temperature
  - NST exhibits flat/intergranular fracture with some solidification features

500ºC; 90 %RA | 600ºC; 95 %RA | 700ºC; 98 %RA | 1000ºC; 99+ %RA | NST=1268ºC ; 0 %RA





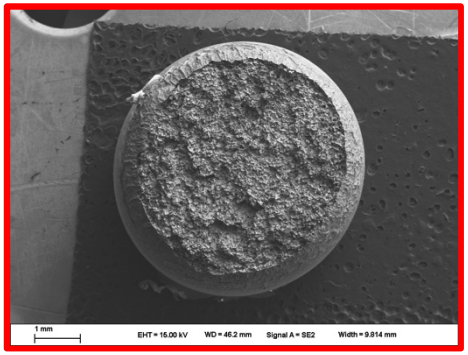


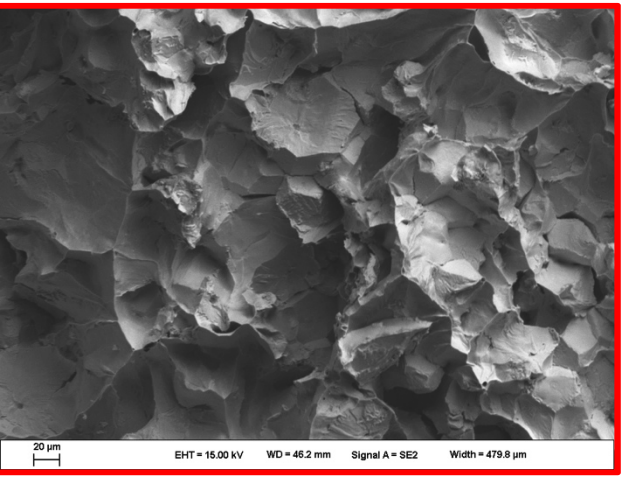


HDT Fractography: On Cooling: Ni-49.6Ti

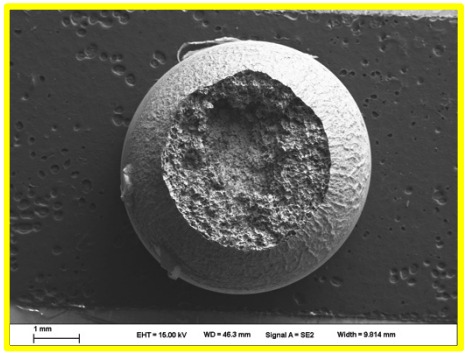
- Precipitous drop in ductility centered ~950ºC on cooling characterized by mixed sample failure mode: ductile rupture + smooth intergranular fracture

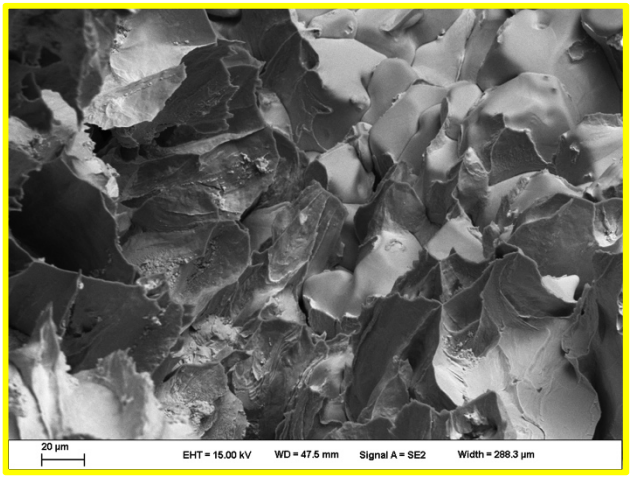
950ºC; 29 %RA



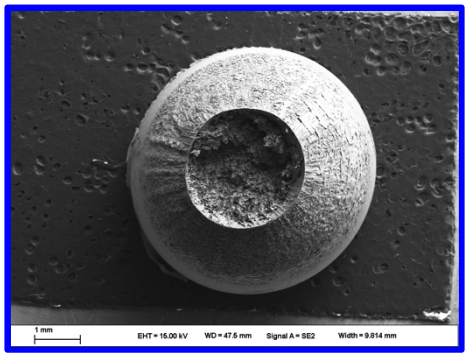


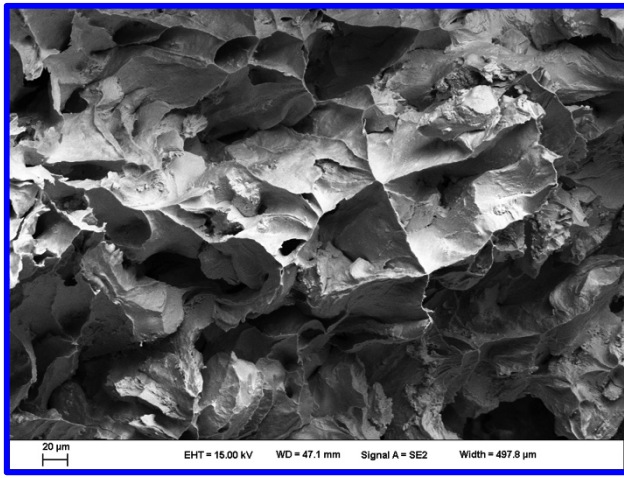
1000ºC; 56 %RA





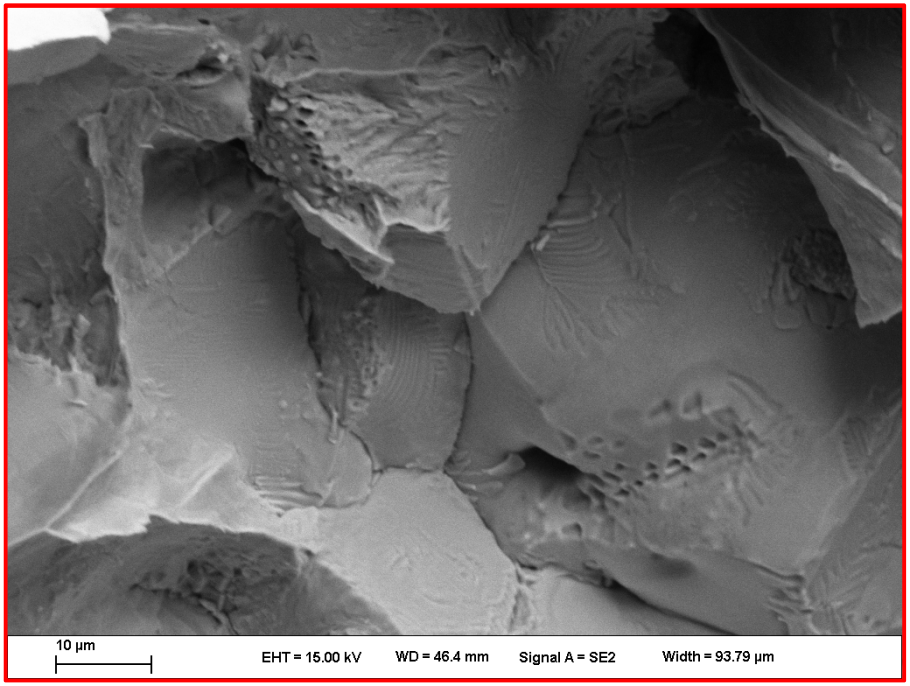
1100ºC; 82 %RA



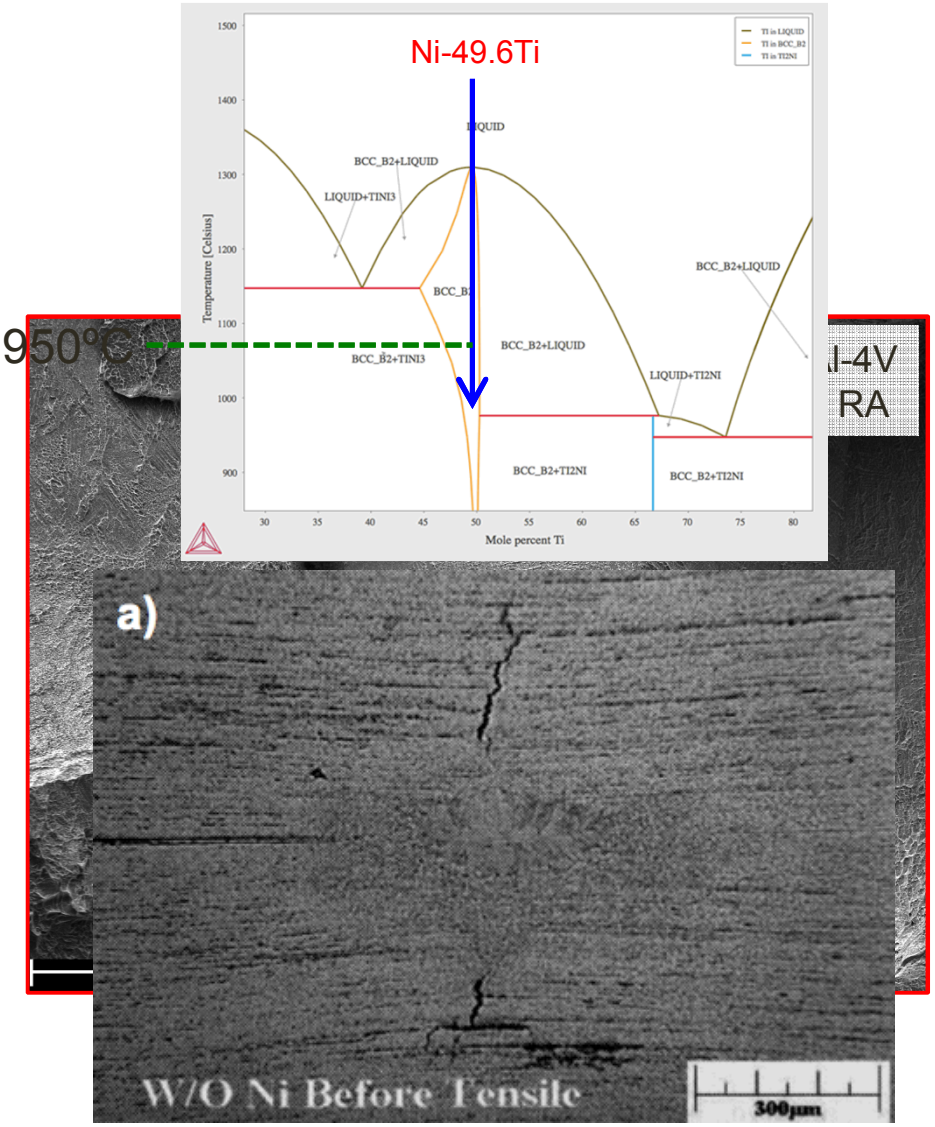


Further work required to understand on-cooling ductility dip for Ni-49.6Ti

Ni-49.6Ti
950ºC; 29% RA



Little evidence of local ductility at grain boudaries

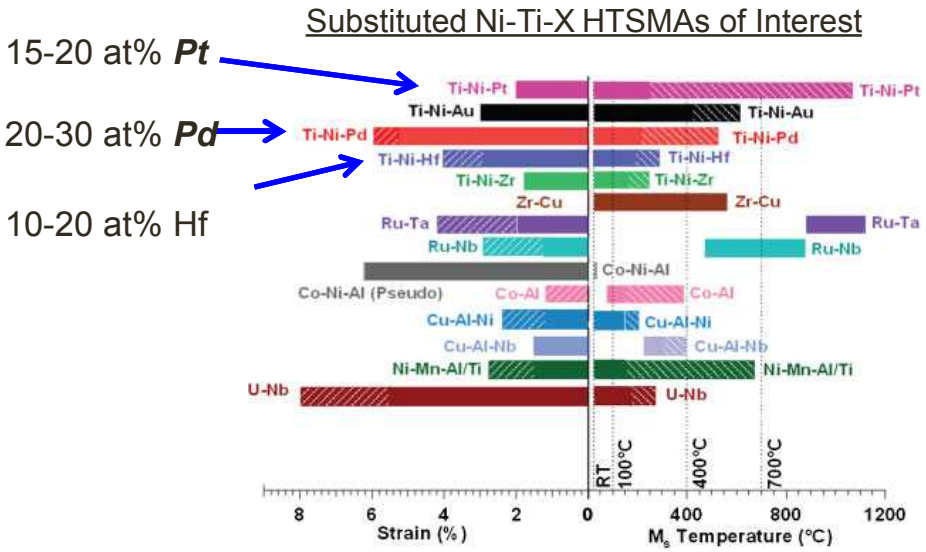


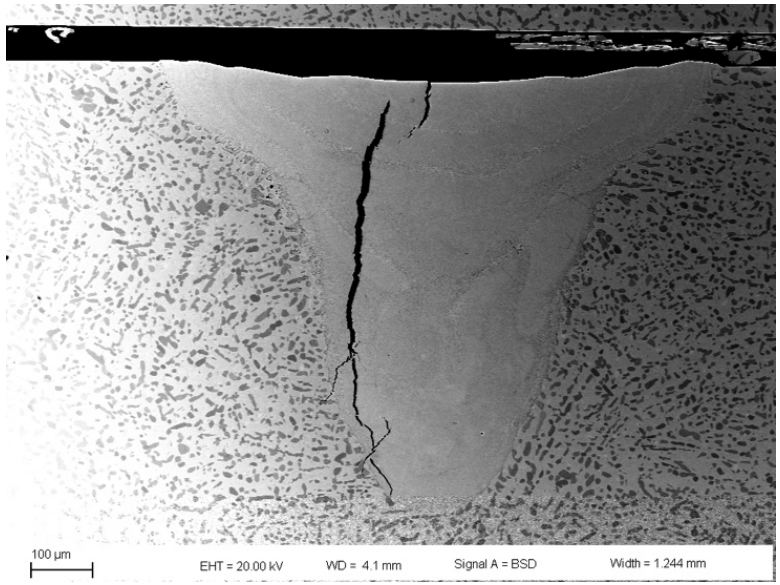
Further characterization will provide insight into HAZ cracking observed in other studies

Rodelas, J.M., Hot Ductility of Near-Alpha and Alpha + Beta Titanium Alloys. TMS 2011, San Diego, CA, USA. March, 2011.
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.

#3 SMA Solidification Crack Susceptibility

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



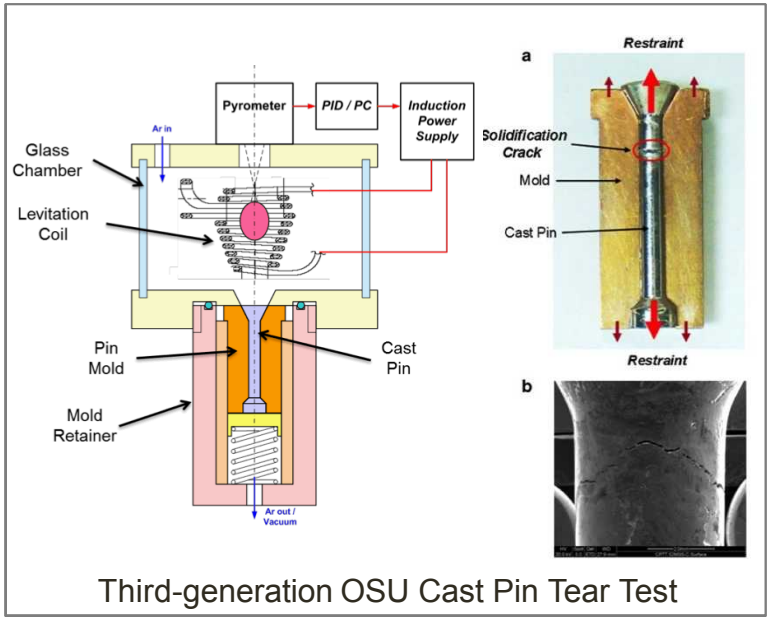


Solidification crack in Ni-Ti-Pt HTSMA laser weld

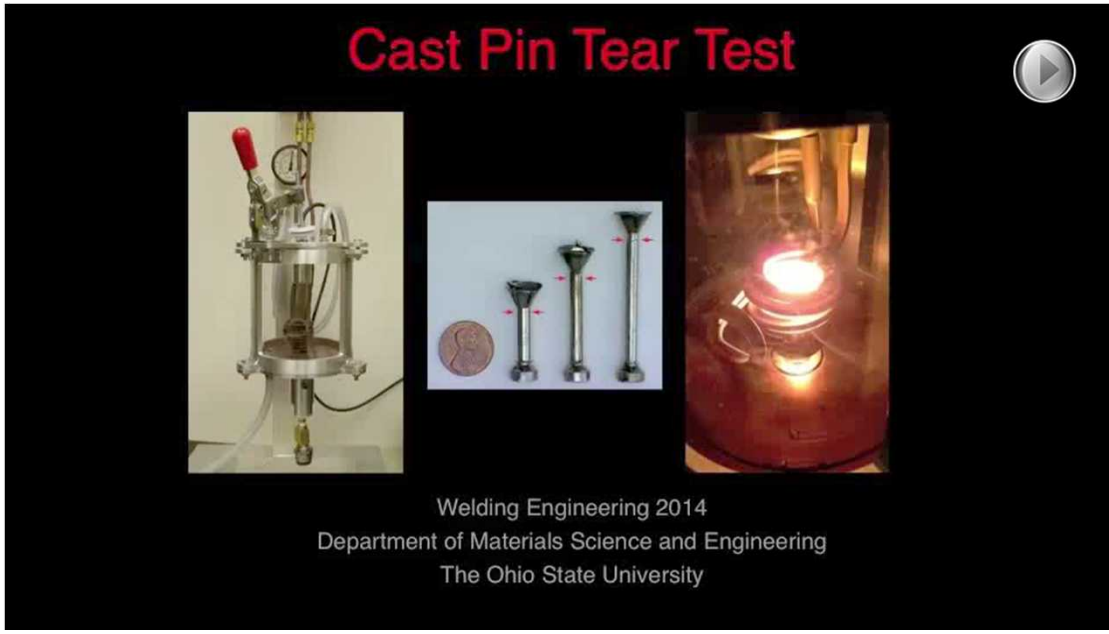
- Large quantities of testable product forms is cost prohibitive

University Partnership 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

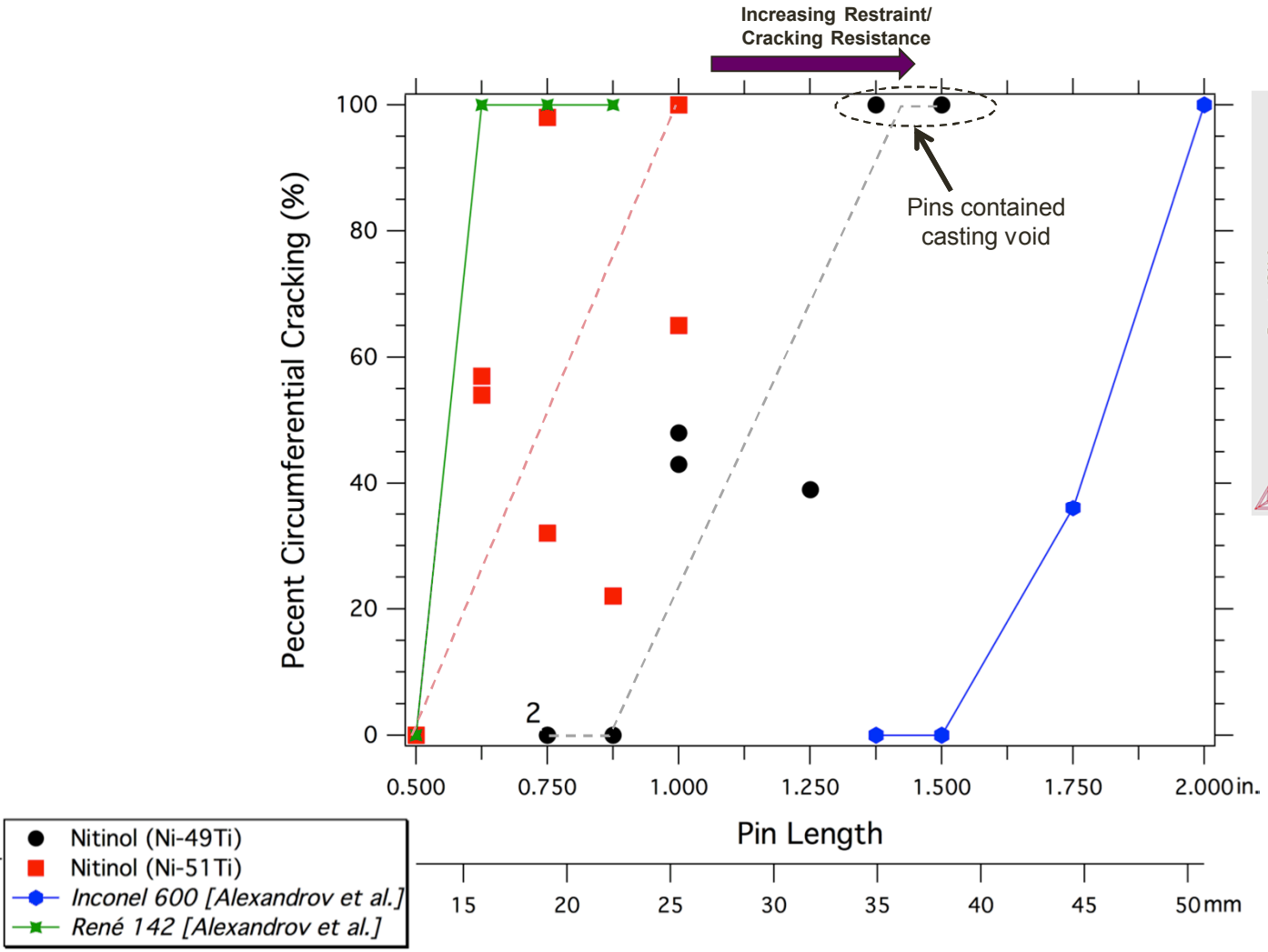


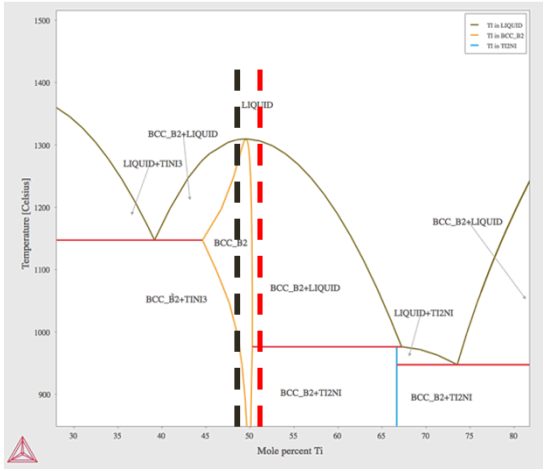
Third-generation OSU Cast Pin Tear Test



SMA CPTT Results

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

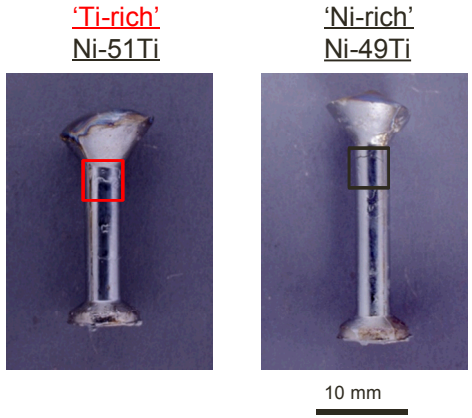


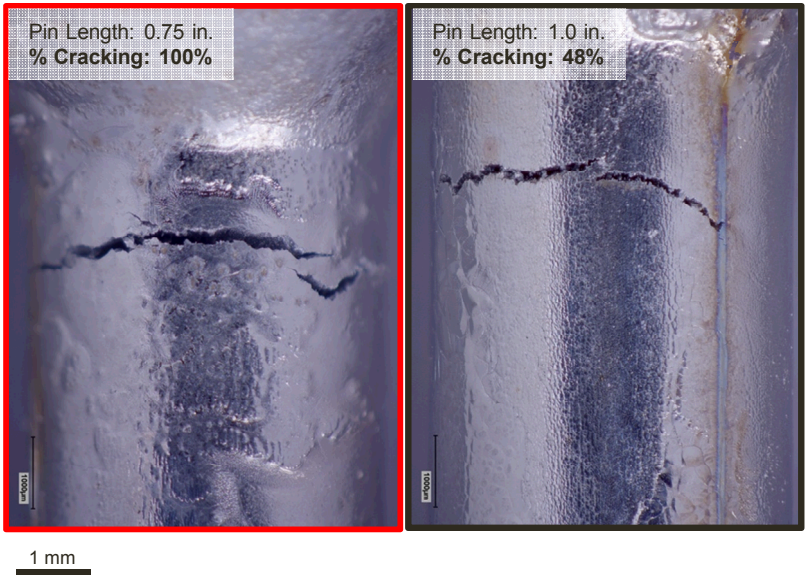


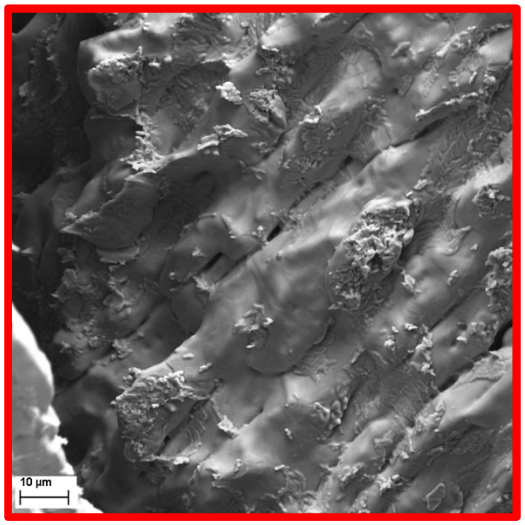
- Non-equilibrium (Scheil) solidification temperature ranges:
  - 161ºC (Ni-49Ti)
  - 335ºC (Ni-51Ti)

CPTT Fractography

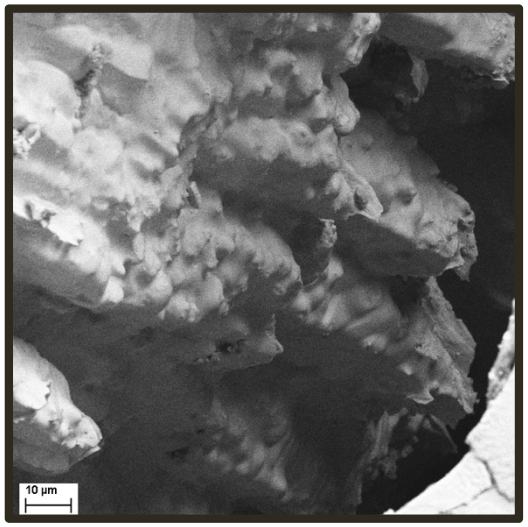
- Solidification features on CPTT fracture surface consistent with solidification cracking



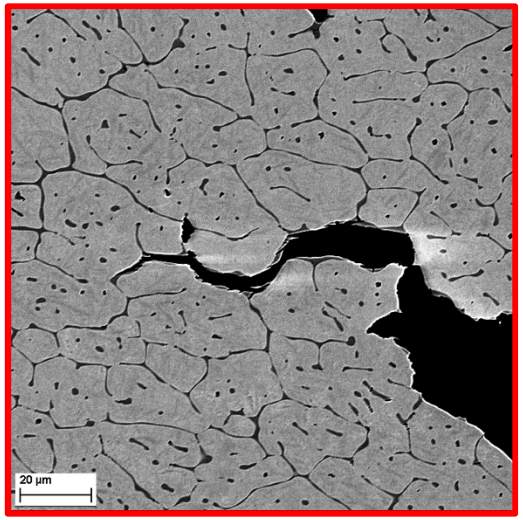




Terminal eutectic phase decorates fracture surface of Ni-51Ti CPTT



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

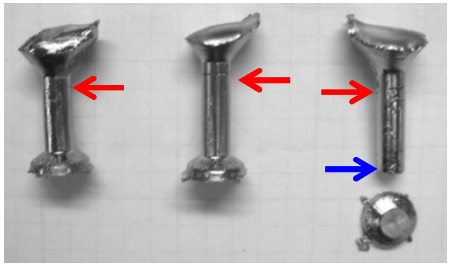


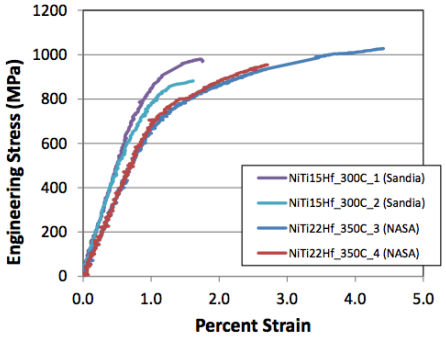
Cross section of Ni-51Ti CPTT reveals fracture along NiTi-Ti_2Ni eutectic

Preliminary HTSMA CPTT Results

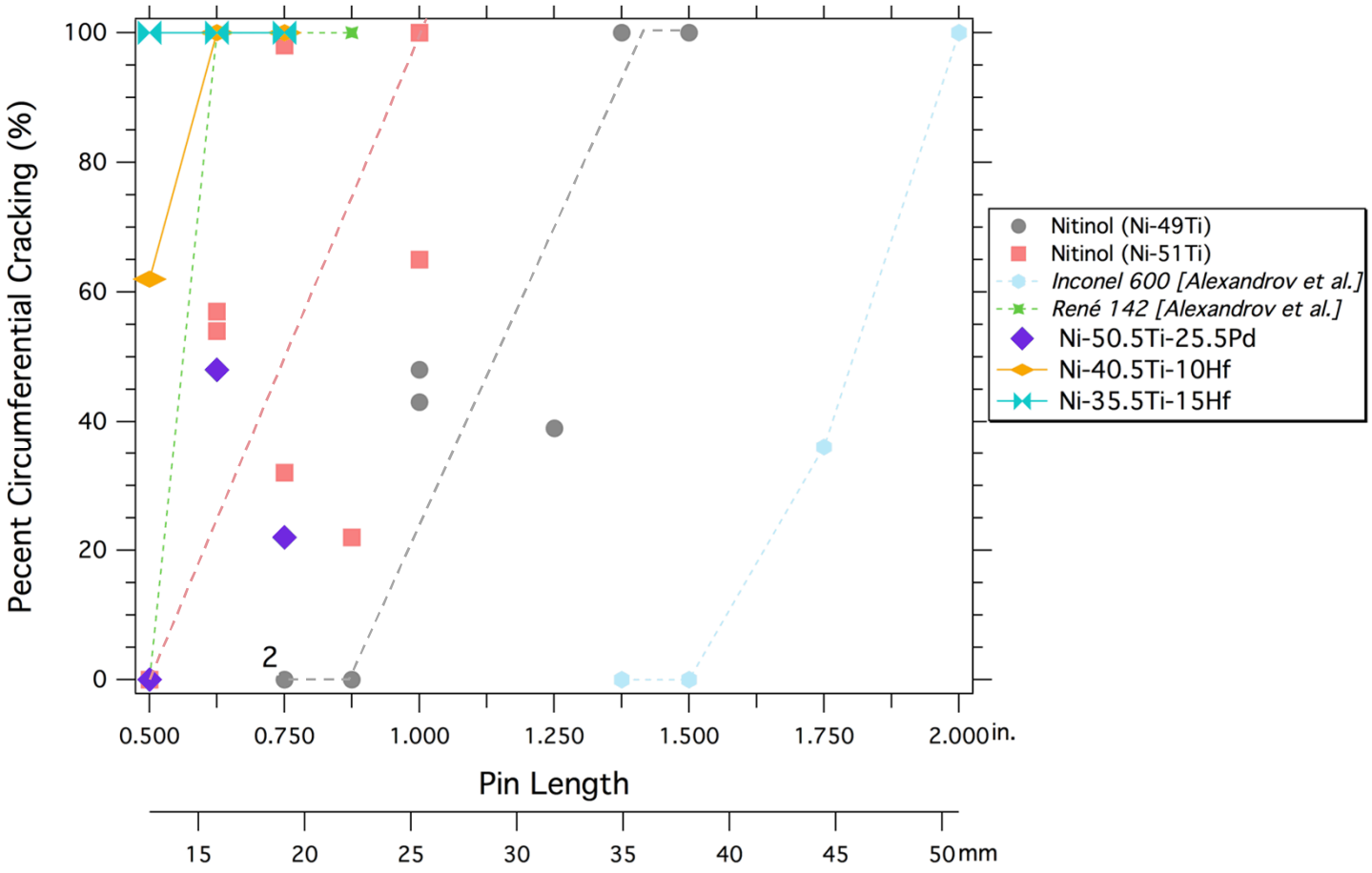
- Ni-Ti-Hf alloys exhibit extensive cracking even for smallest pin mold length
- Ni-Ti-Pd alloy (24.0 Ni – 50.5 Ti – 25.5 Pd) qualitatively similar CPTT response as Ti-rich NiTi

Ni-40.5Ti-10Hf





Ni-Ti-Hf austenite stress-strain behavior (300°C)*



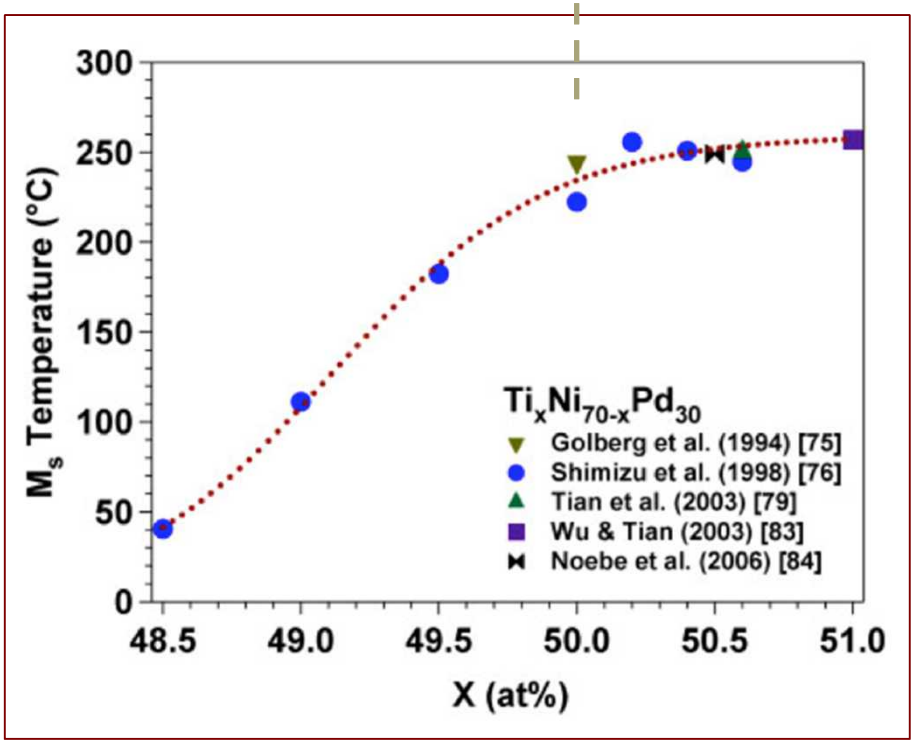
*Internal SNL Report: Susan, DF, et. al. SAND2014-0105. 2014

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-rich
Highly composition-dependent transformation temperature

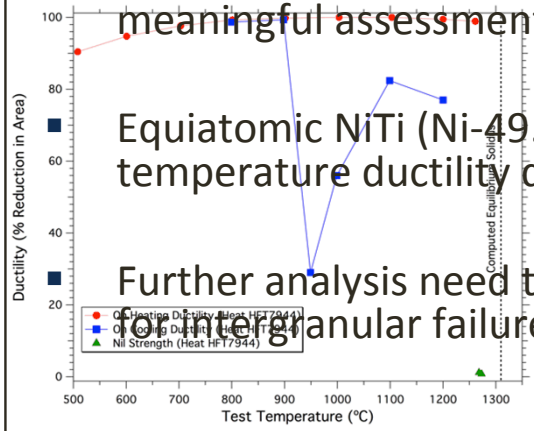
Ti-rich
Composition-independent transformation temperature

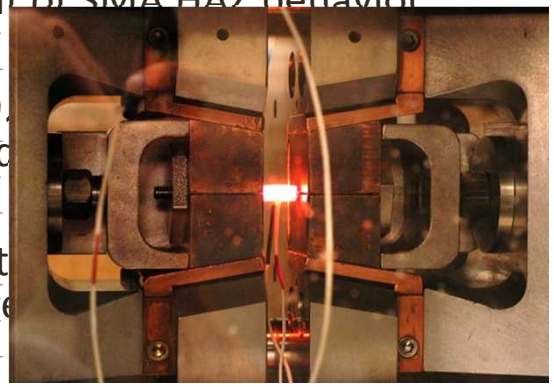


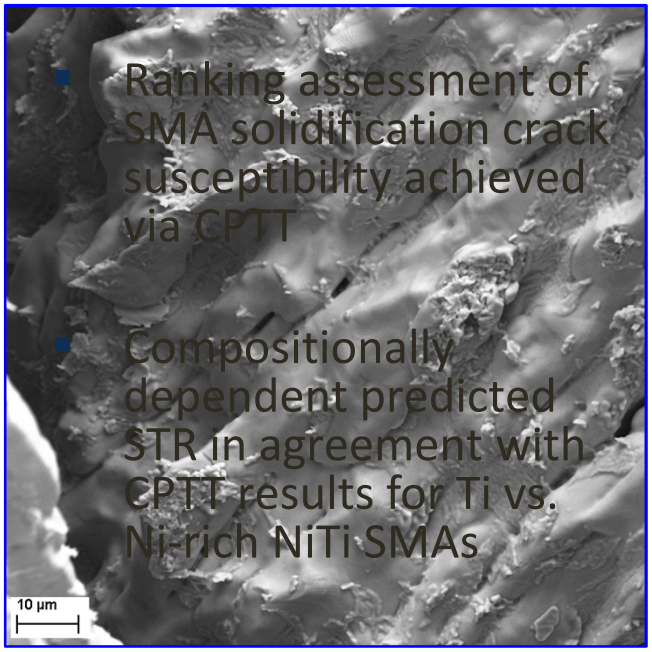
*Internal SNL Report: Susan, DF, et. al. SAND2014-0105. 2014

Concluding Remarks

- Gleeble hot ductility experiments provide basis for meaningful assessment of SMA HAZ behavior
- Equiatomic NiTi (Ni-49.
temperature ductility c
- Further analysis need t
for intergranular failure

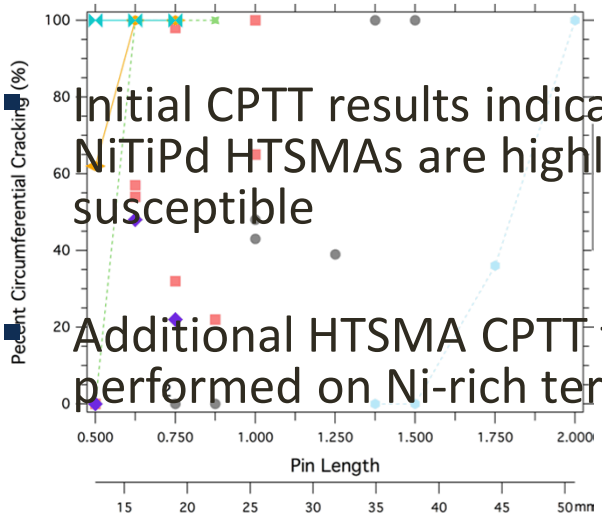






- Ranking assessment of SMA solidification crack susceptibility achieved via CPTT
- Compositionally dependent predicted STR in agreement with CPTT results for Ti vs. Ni-rich NiTi SMAs

- Initial CPTT results indicate Ti-rich NiTiHf and NiTiPd HTSMAs are highly solidification crack susceptible
- Additional HTSMA CPTT testing will be performed on Ni-rich ternary compositions



Acknowledgments

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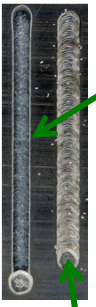
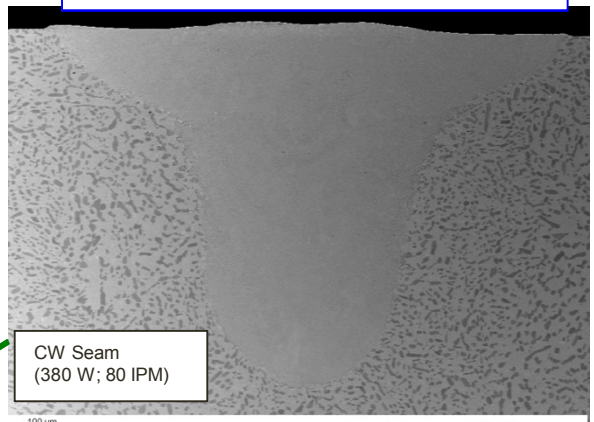
- Special thanks to:
  - The Ohio State University: Welding & Joining Metallurgy Group
    - Dr. Boian Alexandrov
    - Tyler Payton
  - Peter Duran
  - Don Susan
  - Charlie Robino
  - Alice Kilgo
  - Bonnie McKenzie
  - Amy Allen

HTSMA Laser Beam Weld

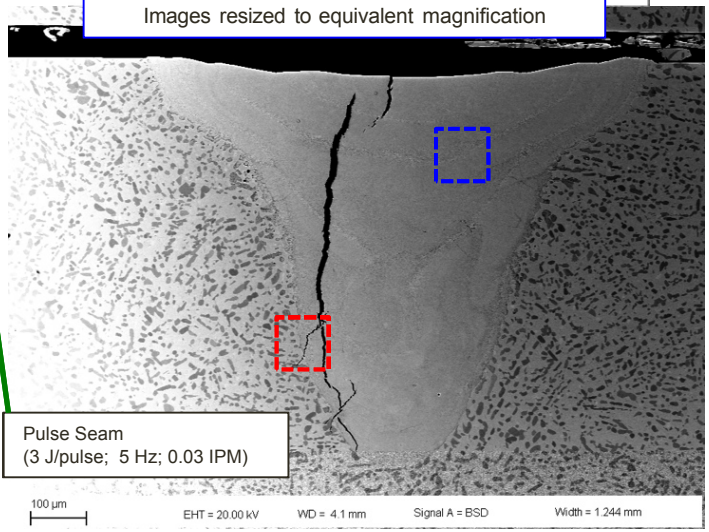
- Autogenous laser welds can be successfully be made on cast Ni-Ti-Pt HTSMAs
- Cracking in pulsed laser welds highlights material process sensitivity

HTSMA: 31.5Ni-50.5Ti-18Pt

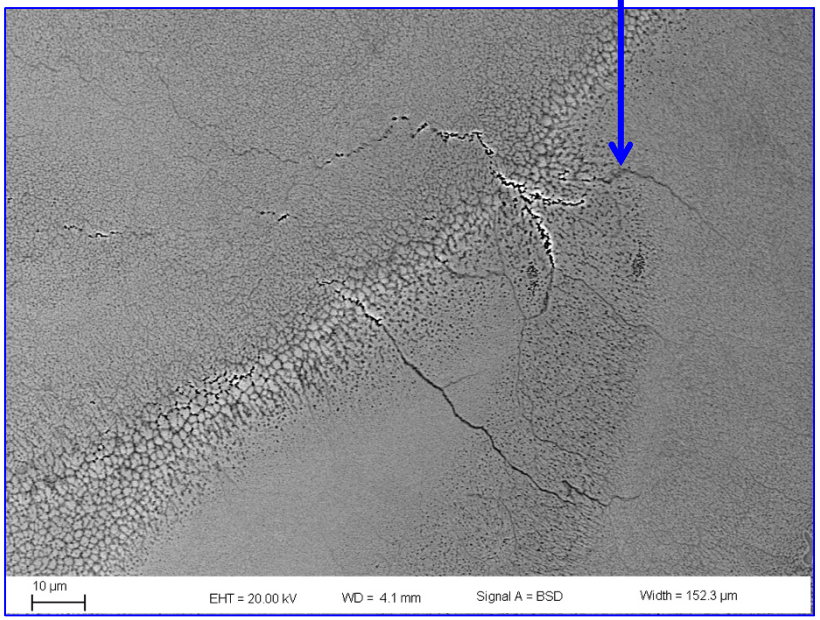


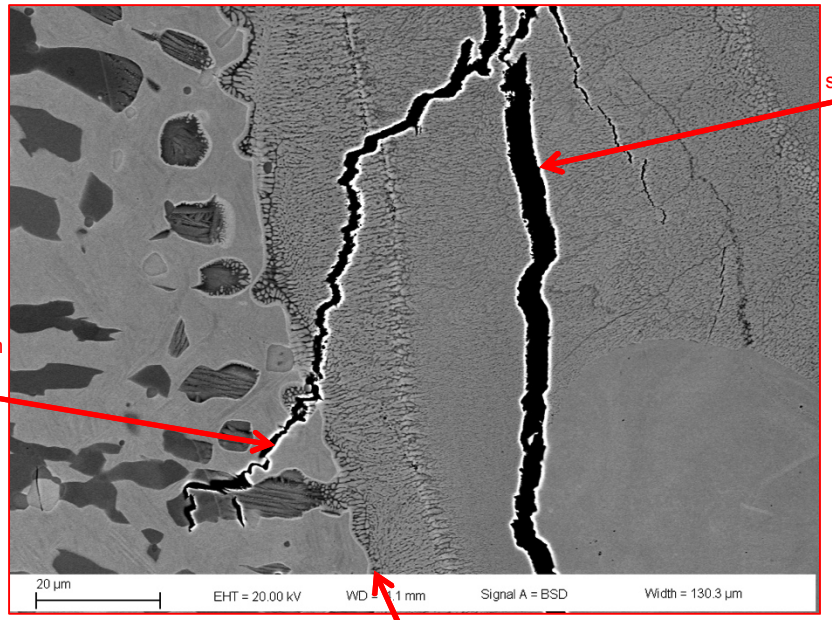


Images resized to equivalent magnification



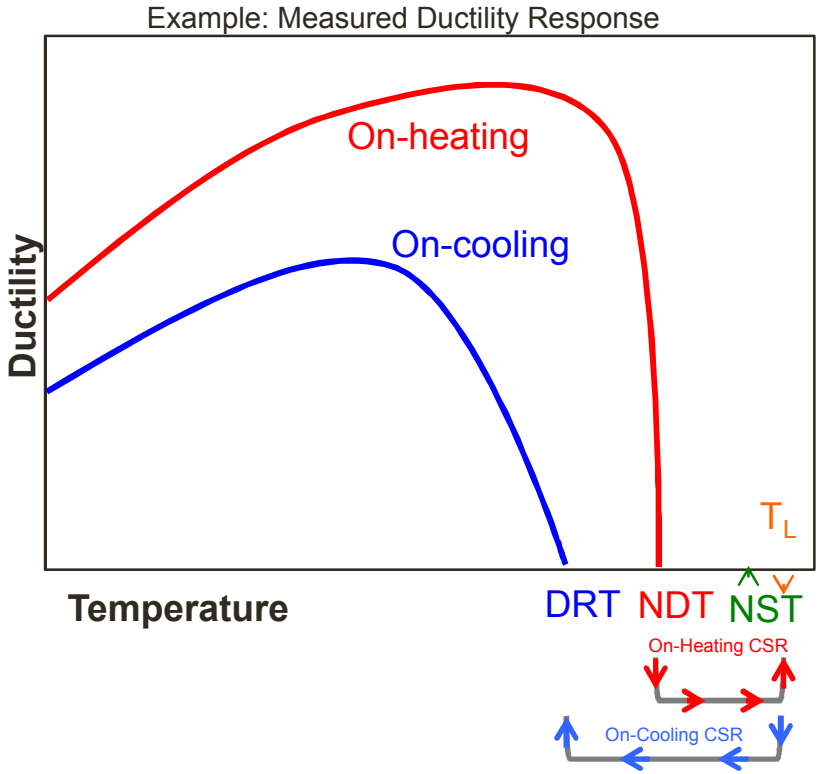
Liquid backfilling of solidification crack along pulse boundary

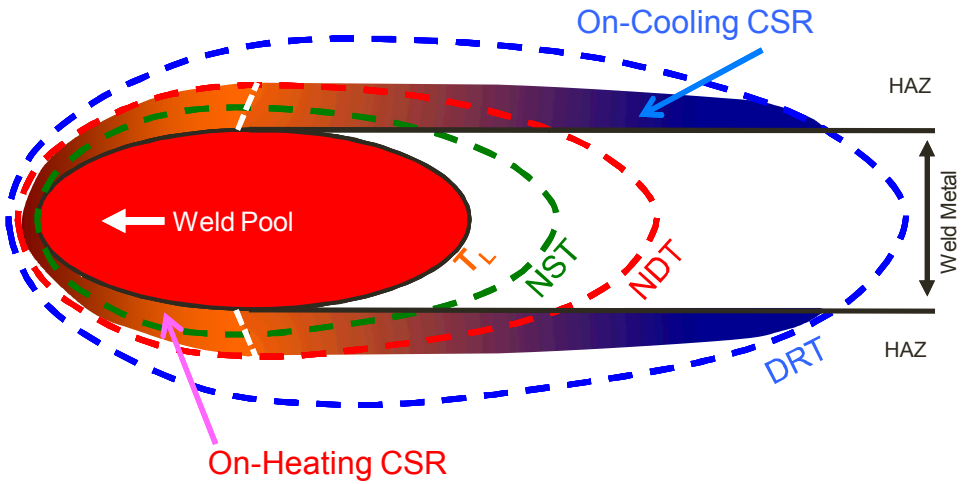




Understanding SMA Heat Affected Zone (HAZ) Behavior

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



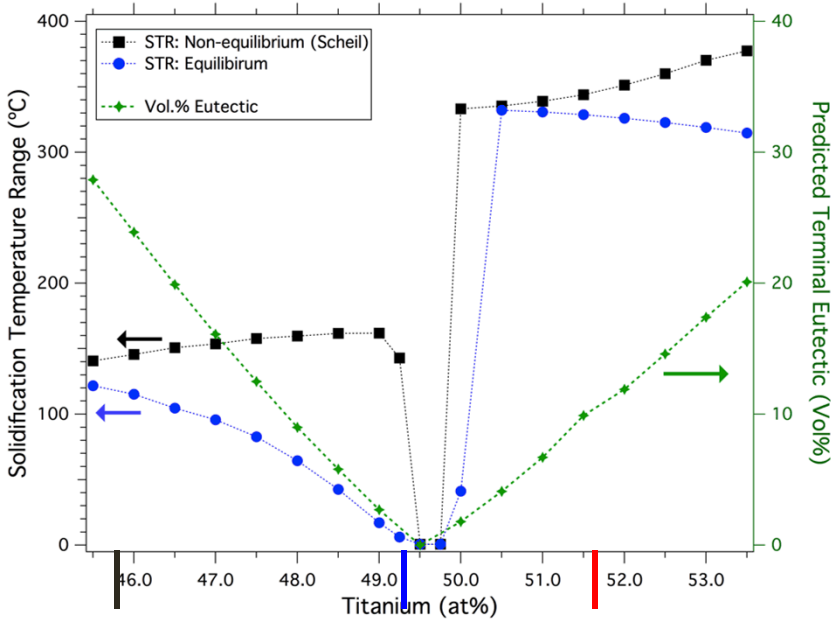


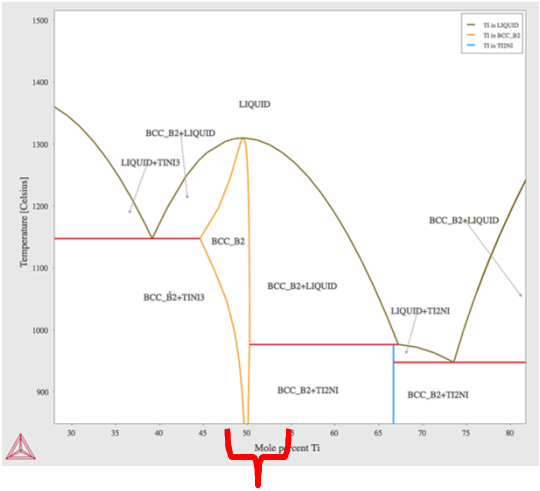
Translation of Measured HDT Temperatures to HAZ Crack Susceptible Regions (CSR)

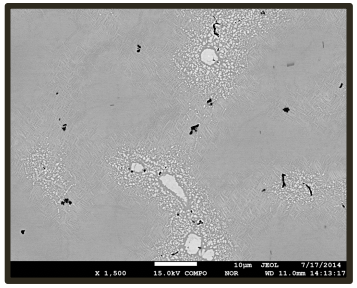
- NST: Nil-strength temperature
  - T at which material cannot support load
- NDT: Nil-ductility temperature
  - T at which material fails with no ductility
- DRT: Ductility recovery temperature
  - T at which ductility recovered on cooling

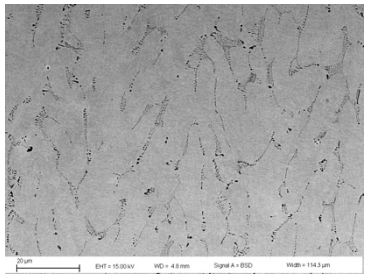
Significant Solidification Temperature Range Compositional Dependence for NiTi SMAs

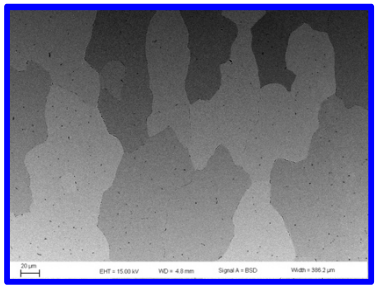
- Ti-rich alloys show large predicted solidification temperature range (STR).
  - Qualitatively agrees with preliminary CPTT tests
- Near-equiatomic and Ni-rich SMAs less prone to solidification cracking

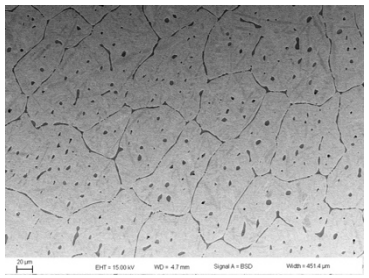


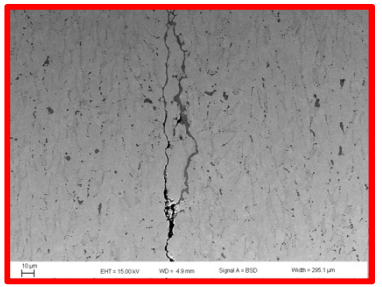












Ni-Rich

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