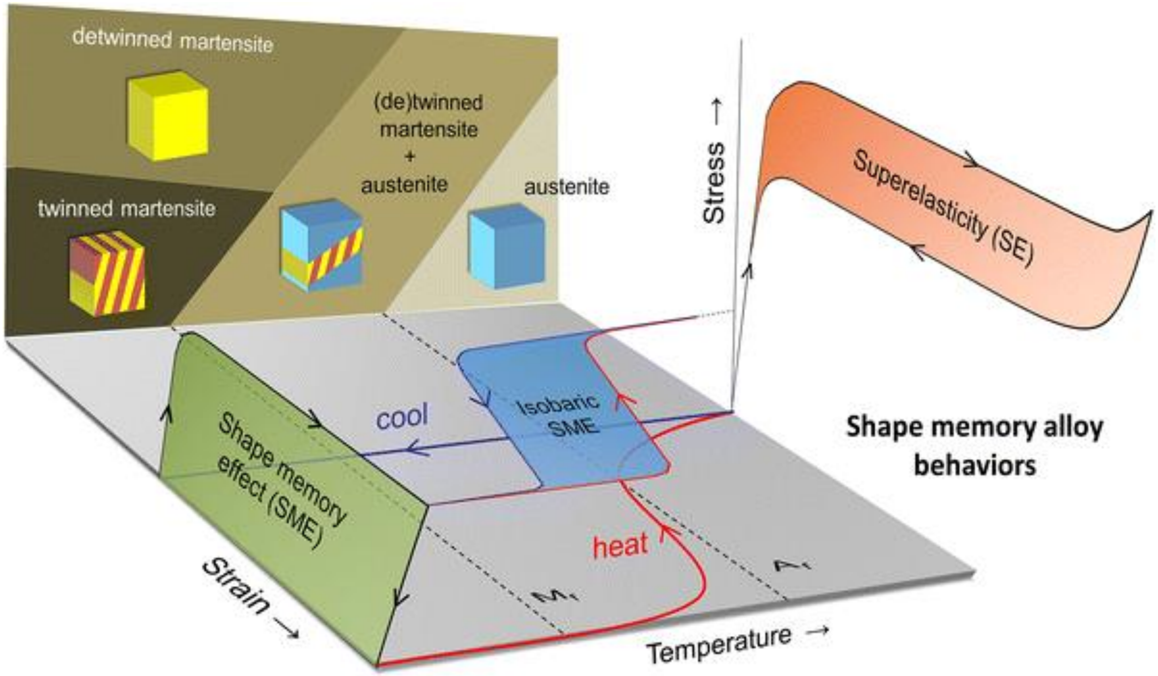
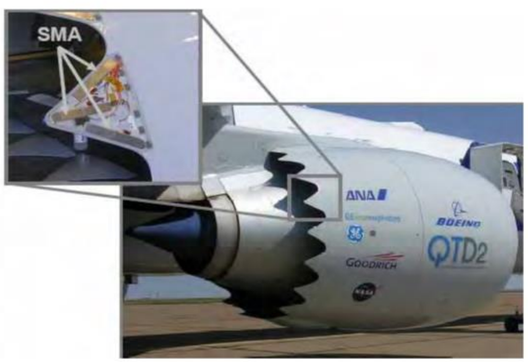
Controlling Martensitic Transformation Characteristics in Defect-Free NiTi Shape Memory Alloys Fabricated Using Laser Powder Bed Fusion and a Process Optimization Framework

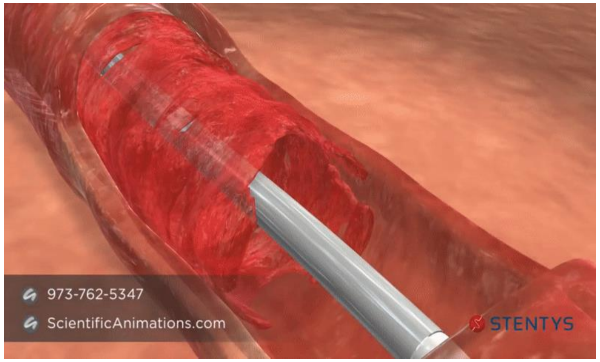
Lei Xue, Cheng Zhang, Kadri Can Atli, Sezer Picak, Bing Zhang,
Alaa Elwany, Raymoundo Arroyave, Dr. Ibrahim Karaman

Department of Materials Science and Engineering
Department of Industrial & Systems Engineering

Shape Memory Alloys



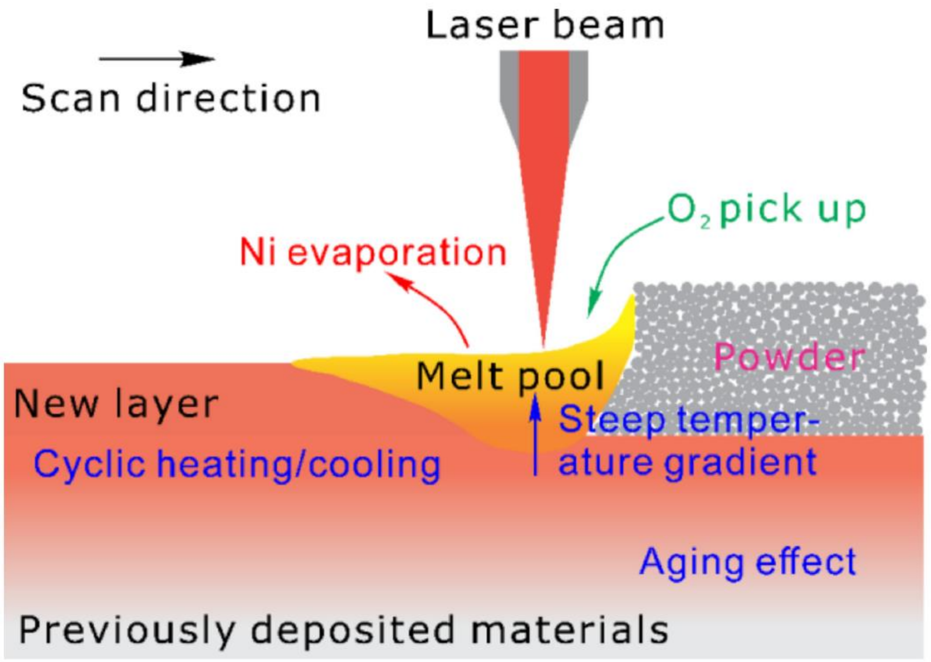




Chowdhury, Piyas, and Huseyin Sehitoglu. "Deformation physics of shape memory alloys–fundamentals at atomistic frontier." *Progress in Materials Science* 88 (2017): 49-88.;
Ji Ma, I. K., R Noebe (2010). "High Temperature Shape Memory Alloys." International Materials Review 55(5): 257-315;https://www.nasa.gov/specials/wheels/; https://www.youtube.com/watch?v=t-zCBKRg7Cs;

Selective Laser Melting

- Conventional machining → Excessive tool wear and burr formation (superior ductility, high toughness and high strain hardening)
- Selective laser melting(SLM) → Better surface finish and geometrical accuracy →Near-net-shape NiTi SMA parts



Wang, Xiebin, Sergey Kustov, and Jan Van Humbeeck. "A short review on the microstructure, transformation behavior and functional properties of NiTi shape memory alloys fabricated by selective laser melting." *Materials* 11.9 (2018): 1683.

Abstract

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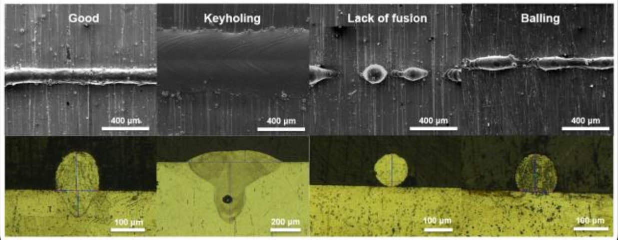
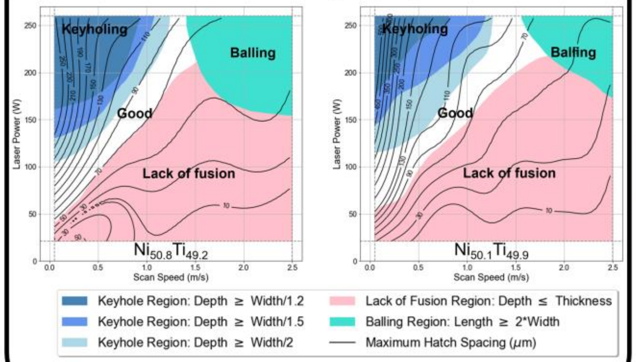
$Ni_{50.8}Ti_{49.2}$ and $Ni_{50.1}Ti_{49.9}$ (at. %)

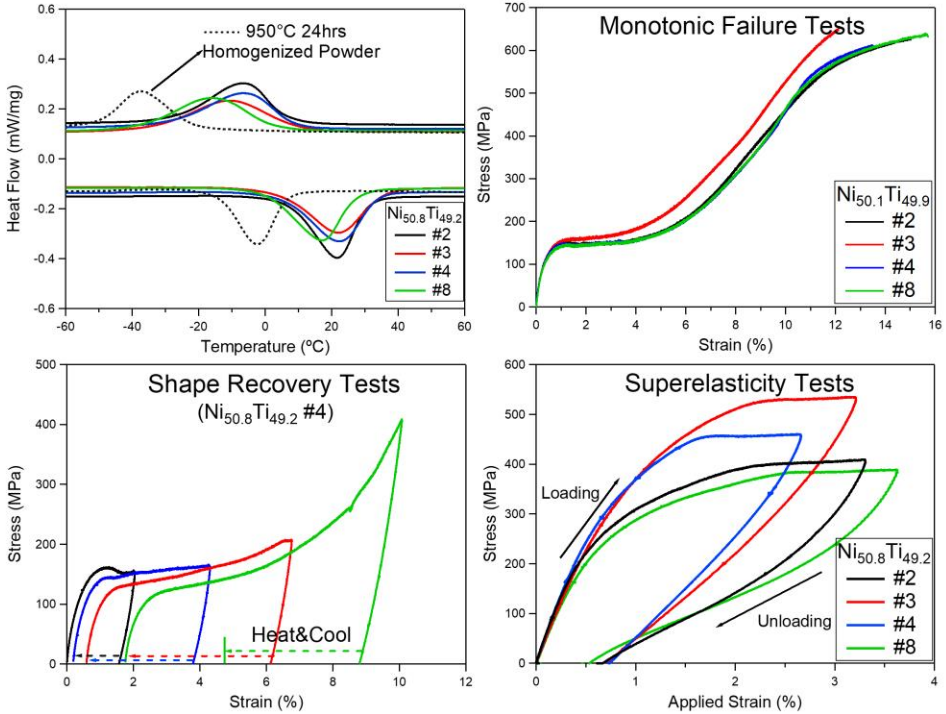
Single Track Experiments

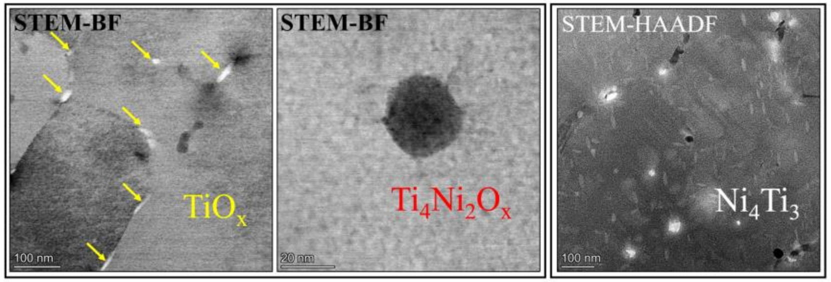


Printability Maps



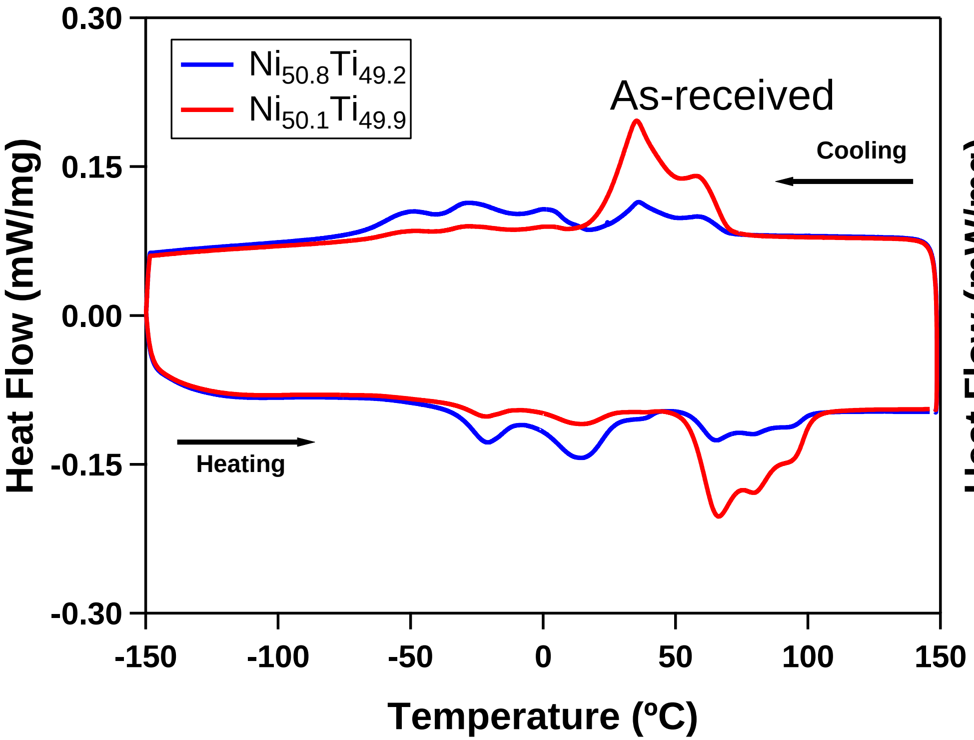
Thermomechanical and Microstructure Characterization



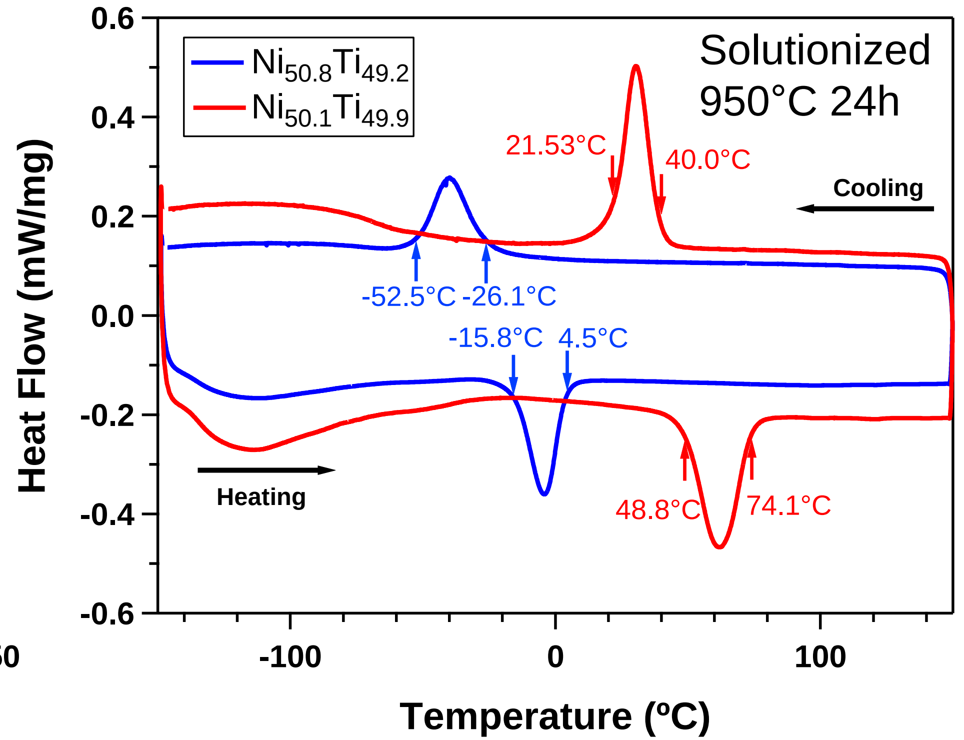


$Ni_{50.8}Ti_{49.2}$ #8 As-printed 400°C 1h Aged

Powder DSC

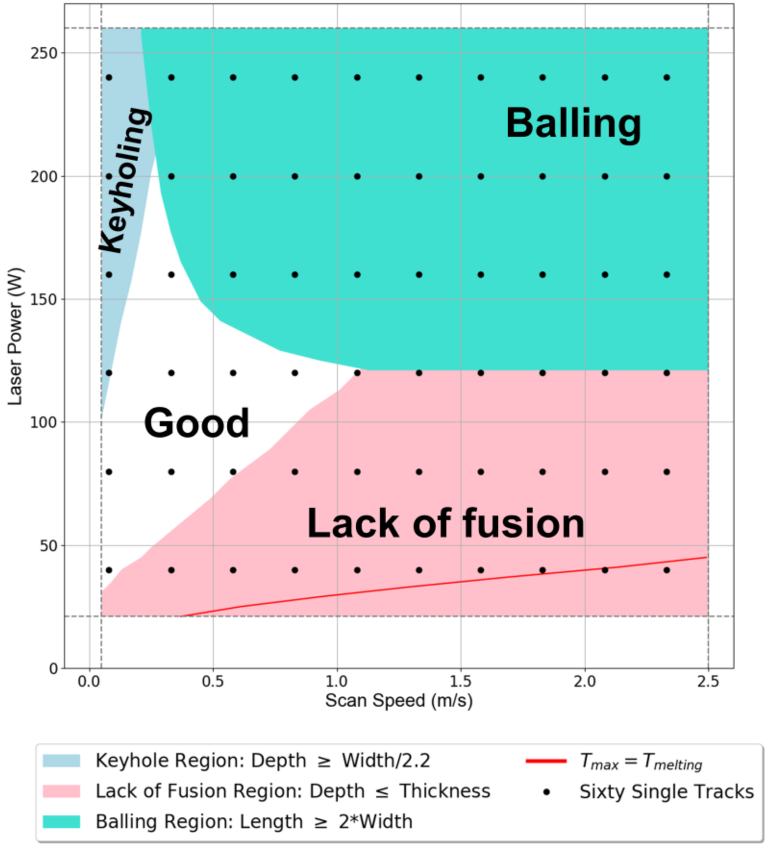


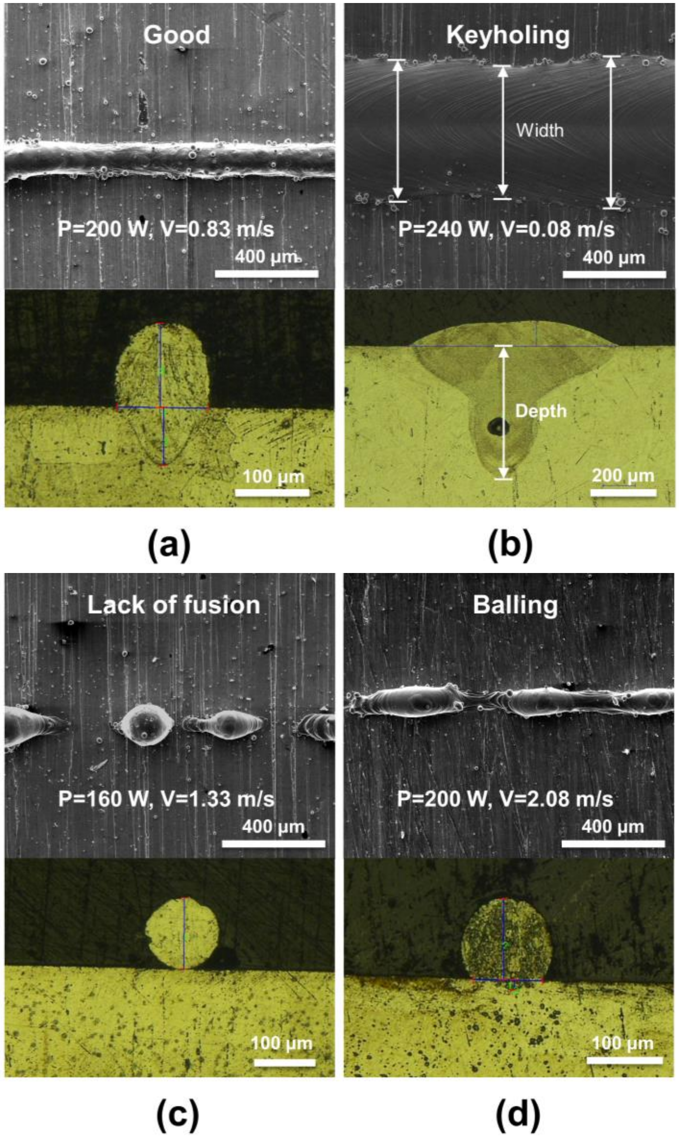
As-received
Ni50.8Ti49.2
Ni50.1Ti49.9
Cooling
Heating
Heat Flow (mW/mg)
0.30
0.15
0.00
-0.15
-0.30
-150
-100
-50
0
50
100
150
Temperature (ºC)



Solutionized
950°C 24h
Ni50.8Ti49.2
Ni50.1Ti49.9
21.53°C
40.0°C
Cooling
-52.5°C -26.1°C
-15.8°C 4.5°C
Heating
48.8°C
74.1°C
Heat Flow (mW/mg)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-100
0
100
Temperature (ºC)

Single Track Sampling





Eager-Tsai (E-T), a thermal conduction model, was used to predict melt pool geometries. And it is computational inexpensive.

Eagar, T. W., and N. S. Tsai. "Temperature fields produced by traveling distributed heat sources." *Welding journal* 62.12 (1983): 346-355.

Single Track Dimensions

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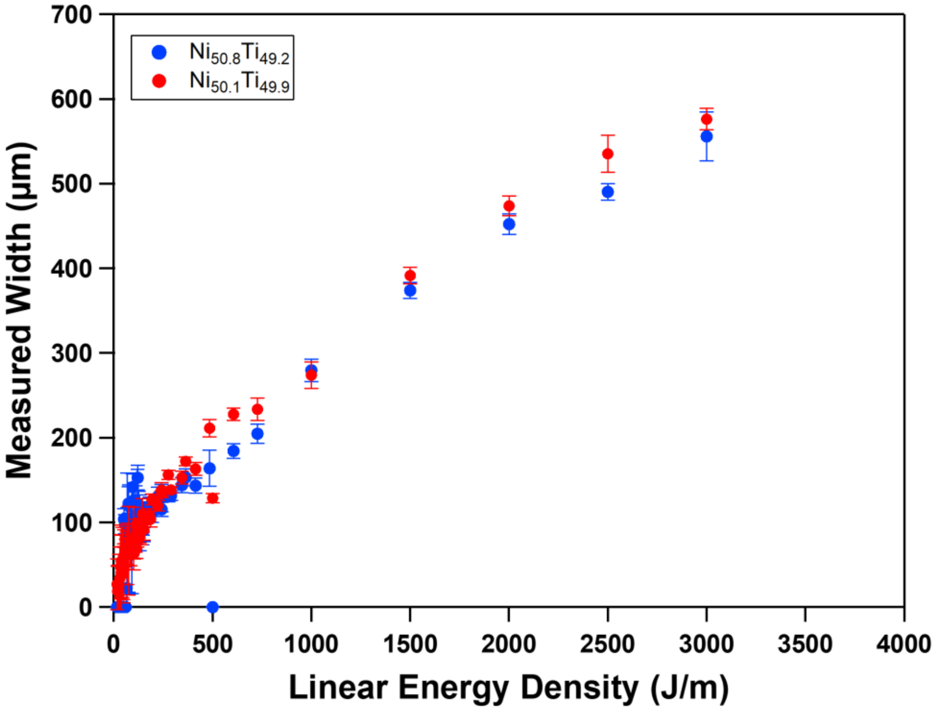
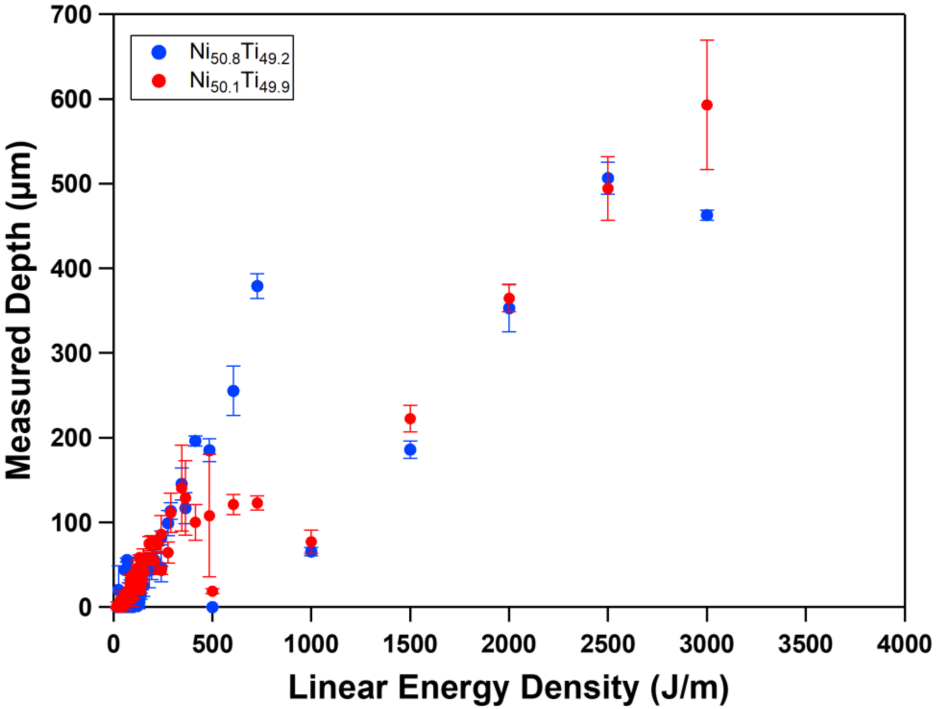
Linear Energy Density (LED)= *P*/*v*



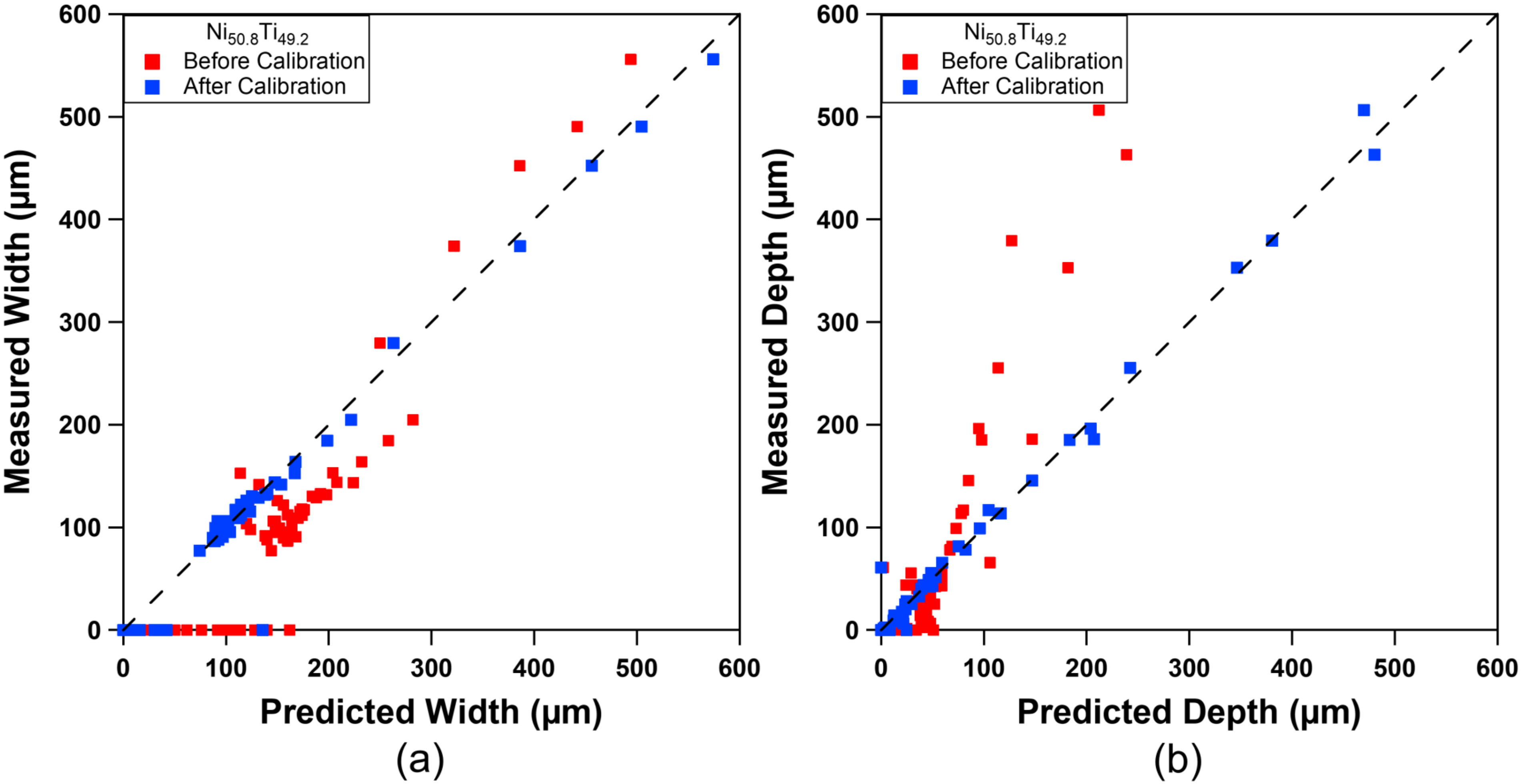
(a)



(b)

These experimental data were used to calibrate the E-T model using a Bayesian statistical calibration.

Statical Calibration



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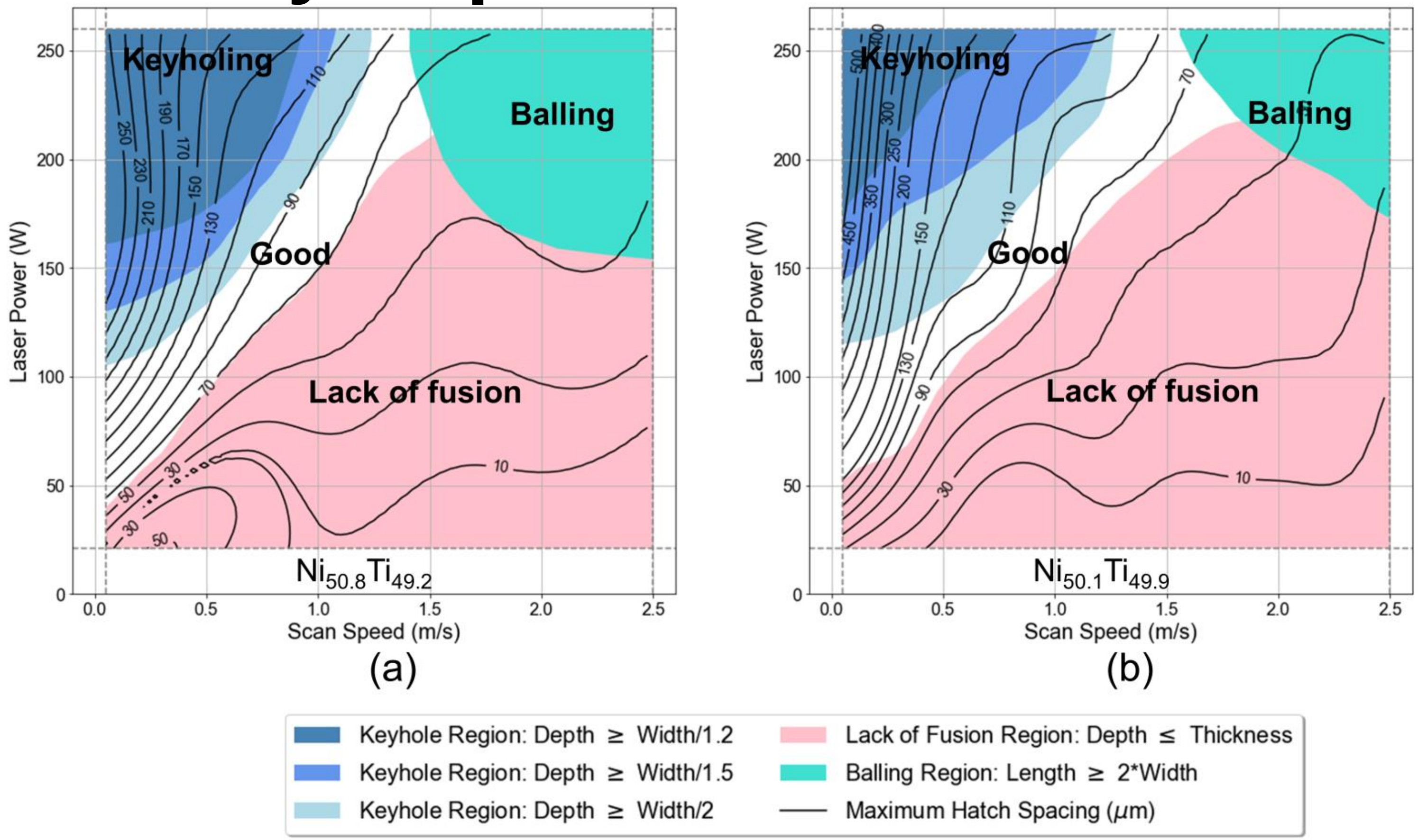
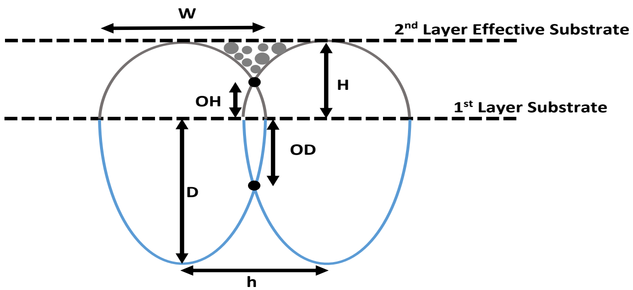
Printability Maps





$$h = W\sqrt{1 - \frac{t}{(t+D)}}$$

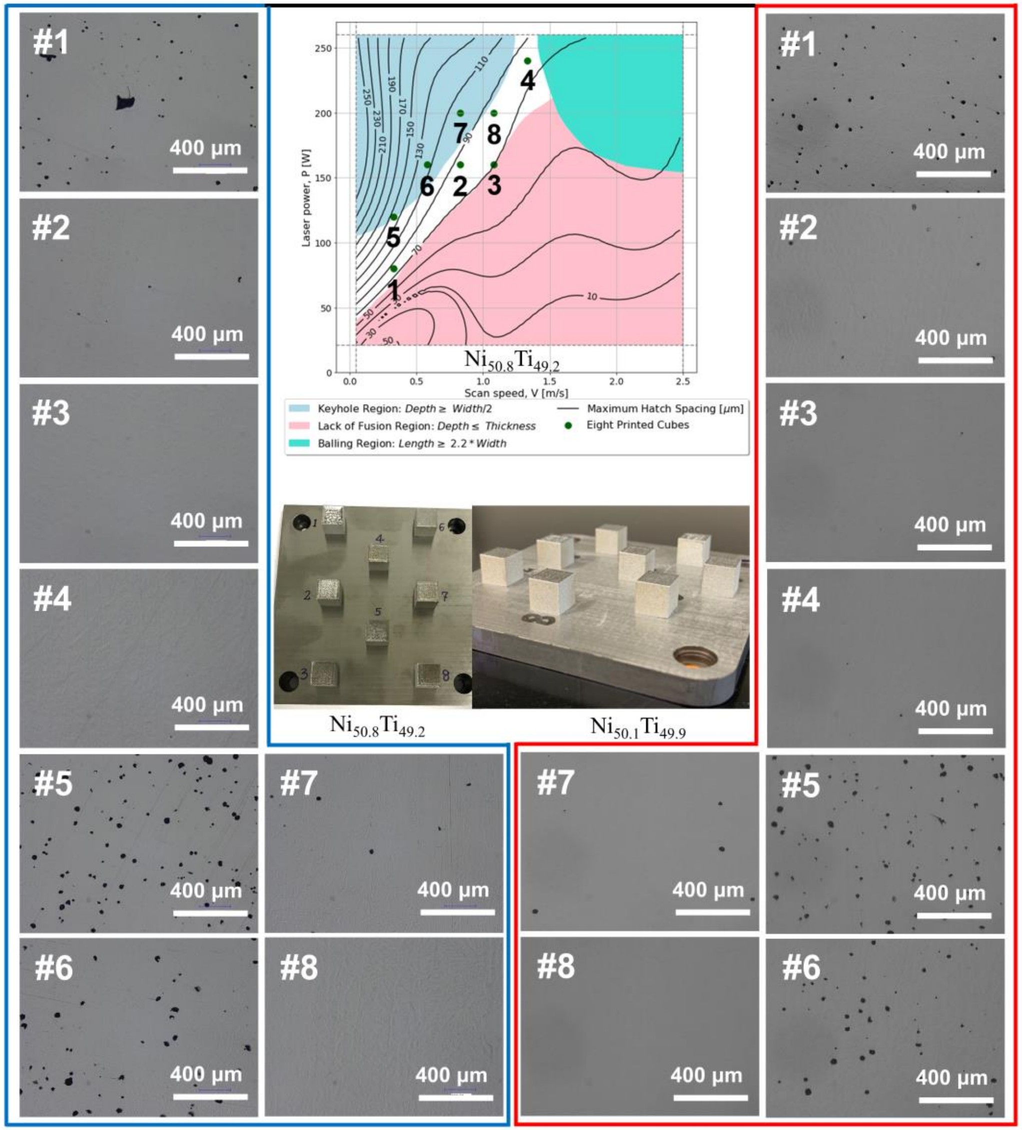
h = Hatch Spacing

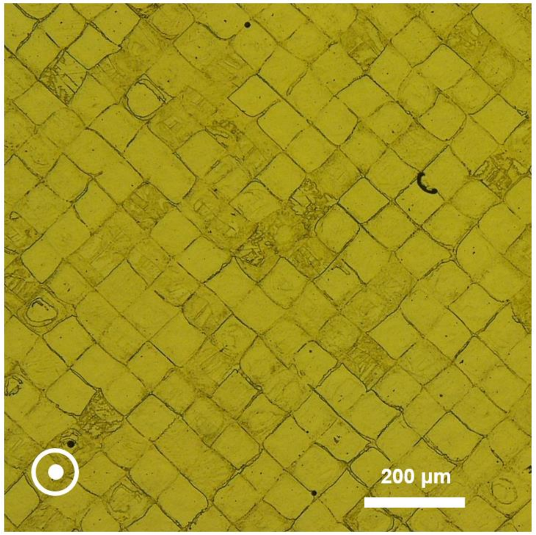
W= Width

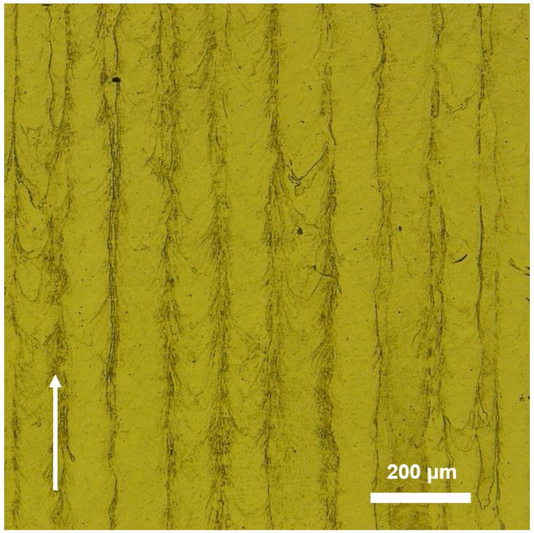
t = Layer Thickness

Seede, Raiyan, et al. "An ultra-high strength martensitic steel fabricated using selective laser melting additive manufacturing: Densification, microstructure, and mechanical properties." *Acta Materialia* 186 (2020): 199-214.

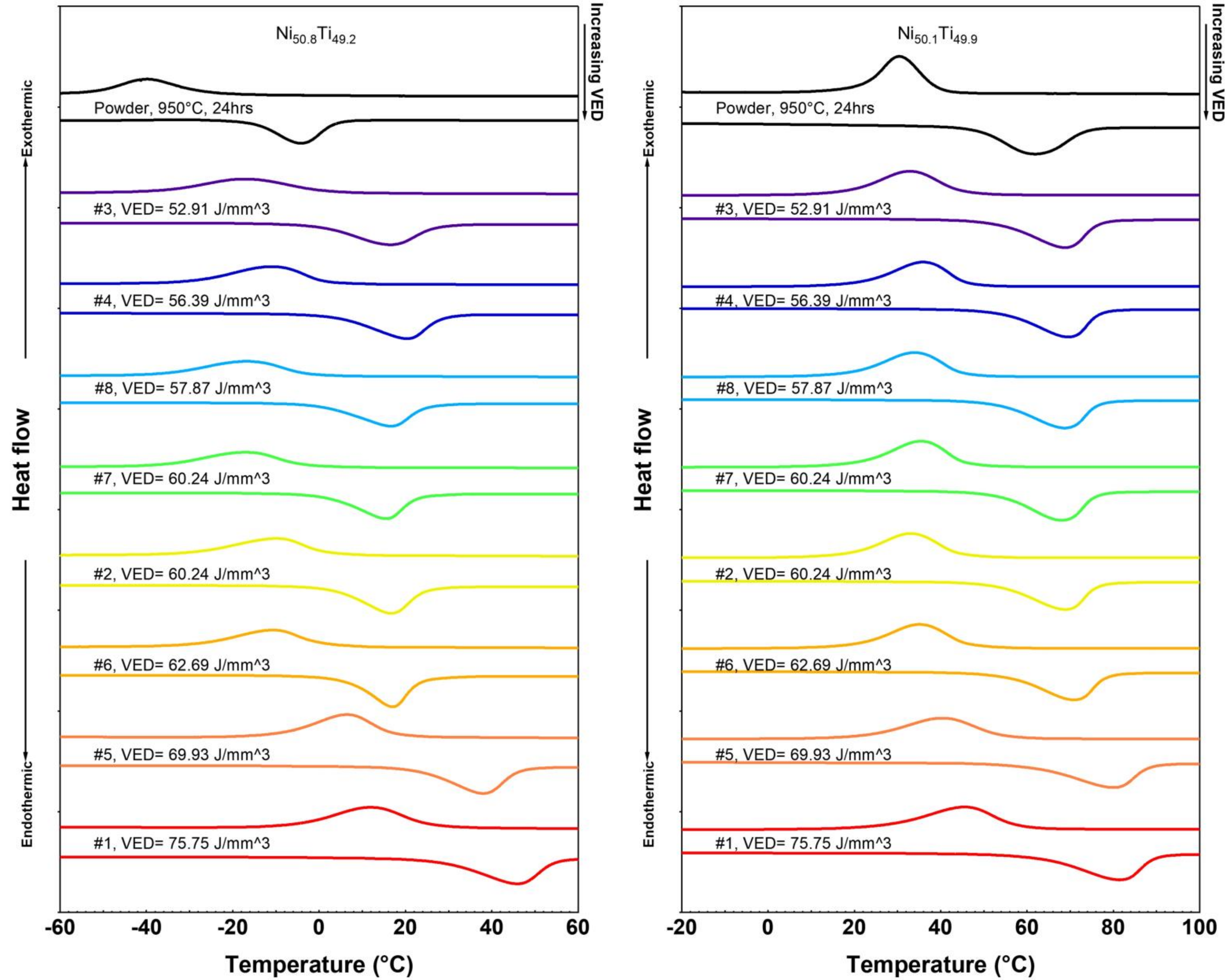
Cubic Prints



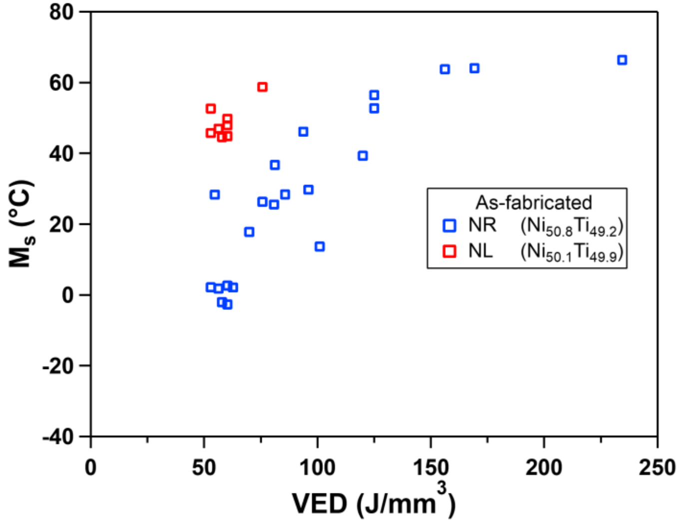




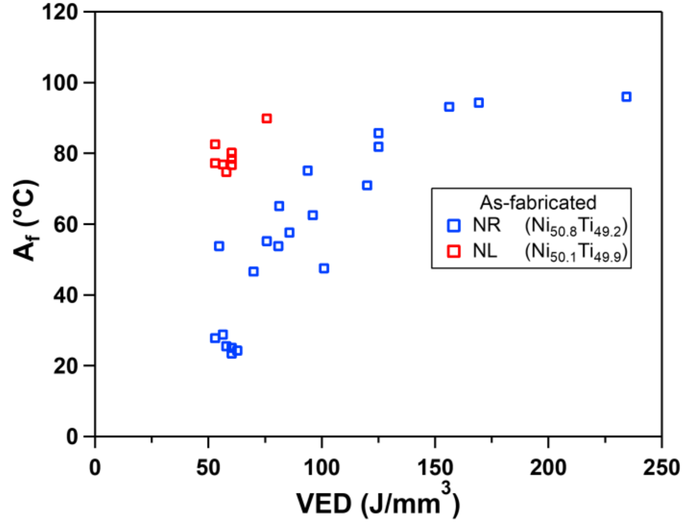
DSC Results of Cubic Prints



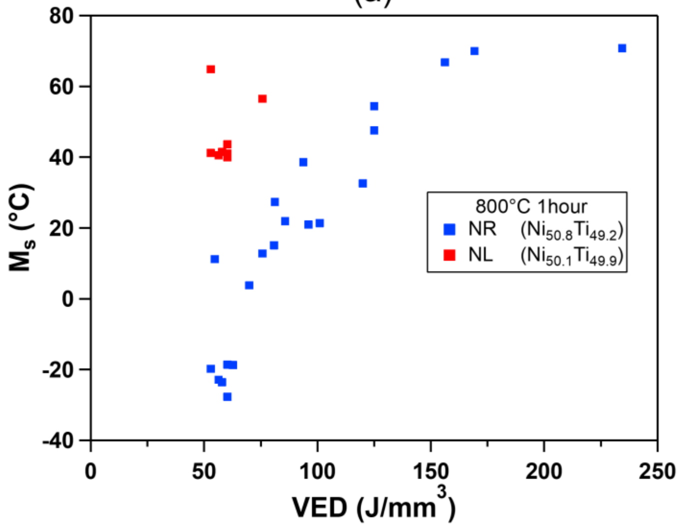
Transformation temperatures vs. VED



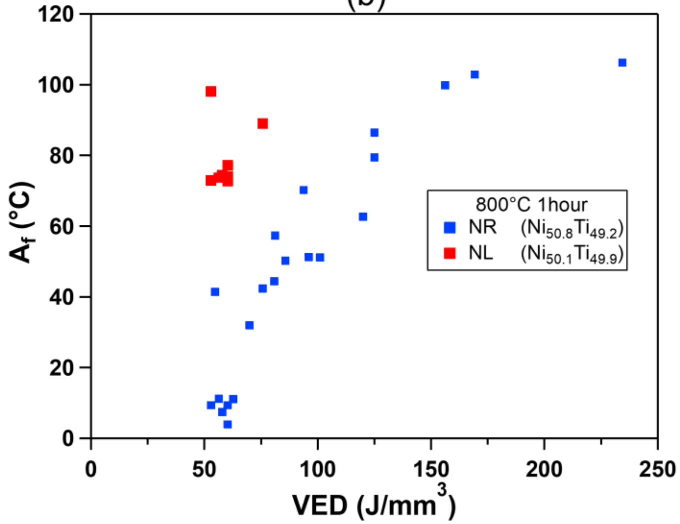
(a)



(b)



(c)

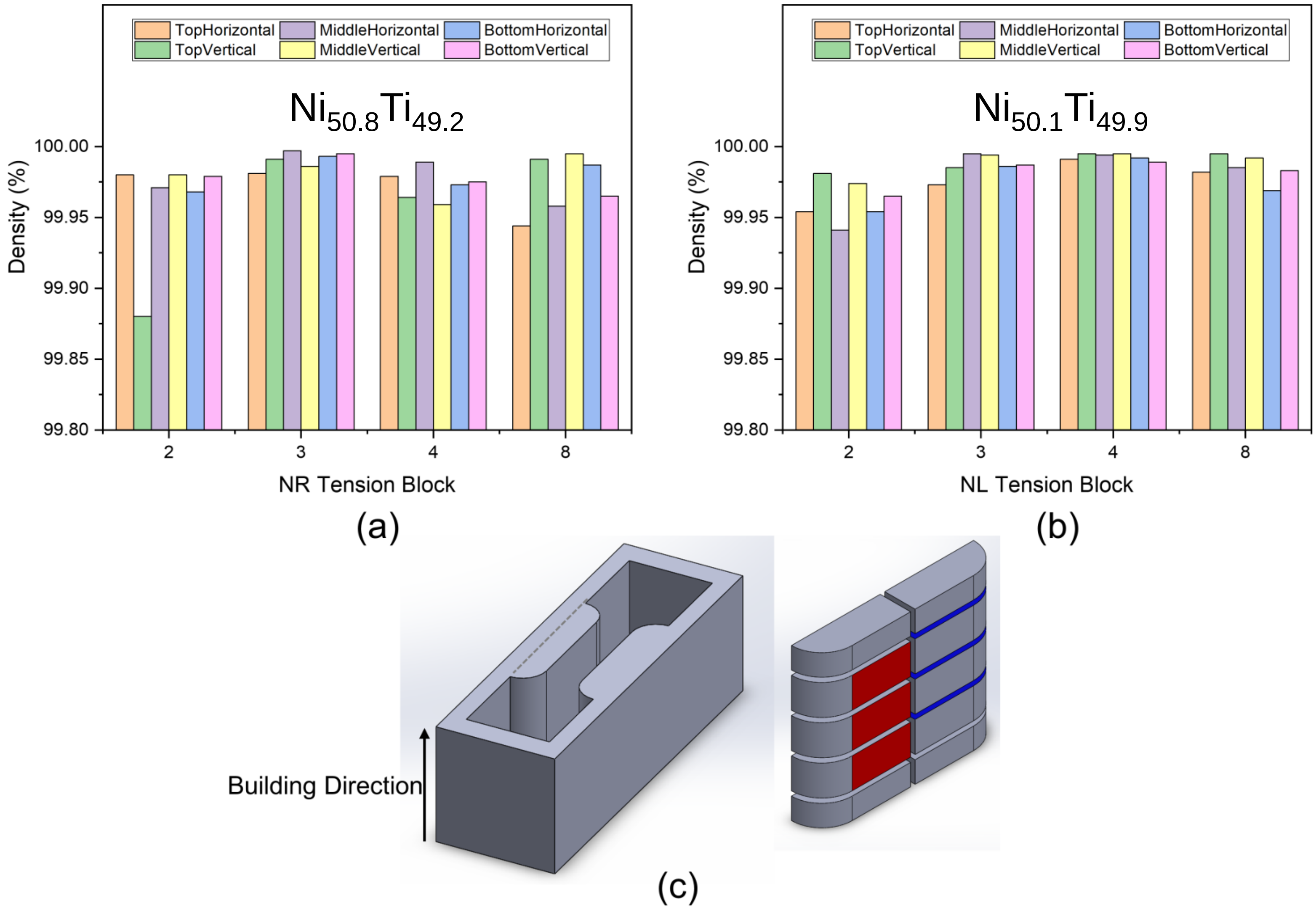


(d)

VED= P/vht

Transformation temperatures are sensitive to the volumetric energy density.

Tensile Blocks



Almost fully dense 30 × 10 ×10 mm^3 rectangular prisms were fabricated.

Monotonic Tensile Test

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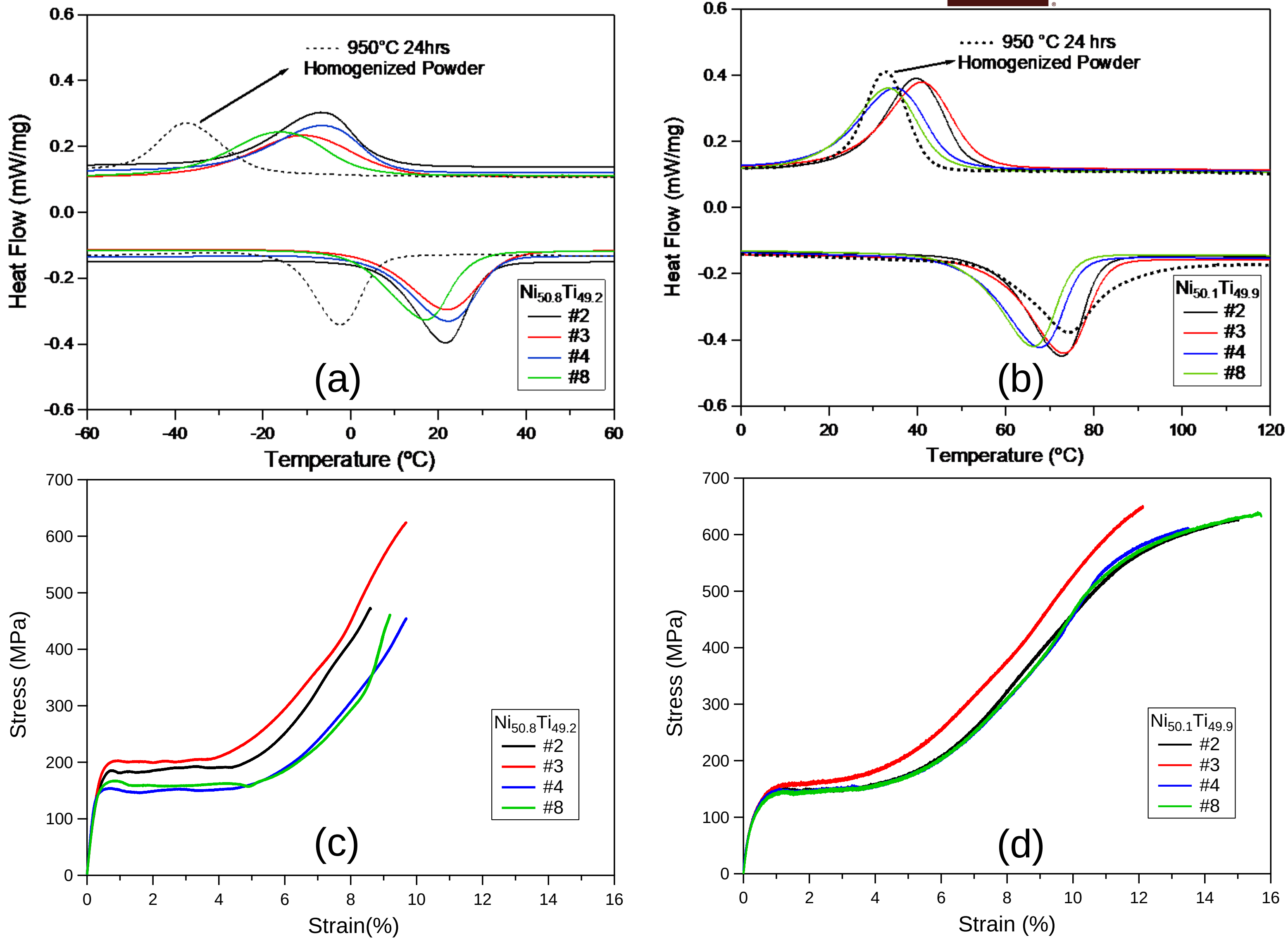
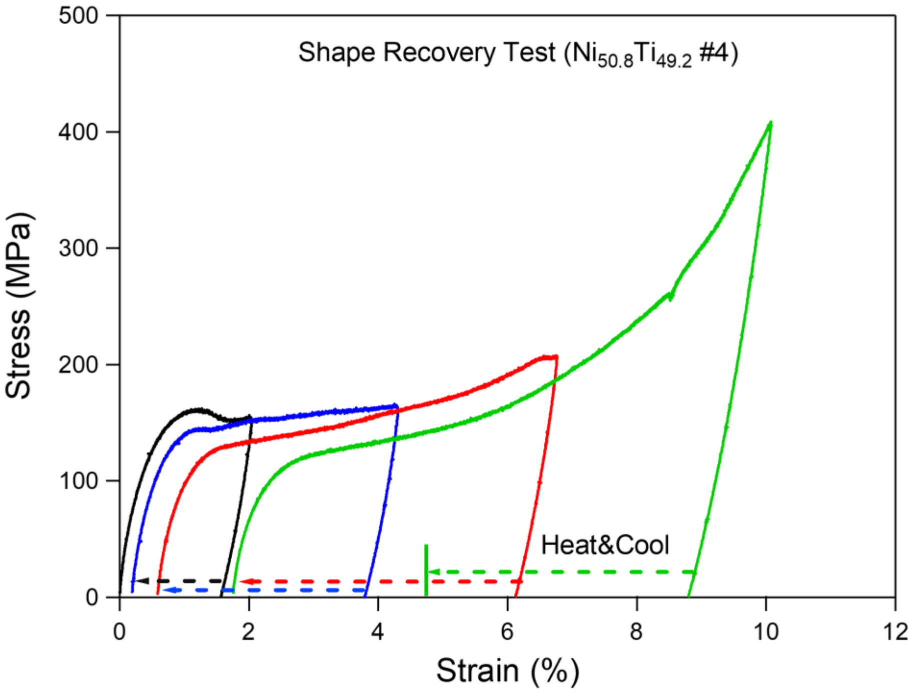
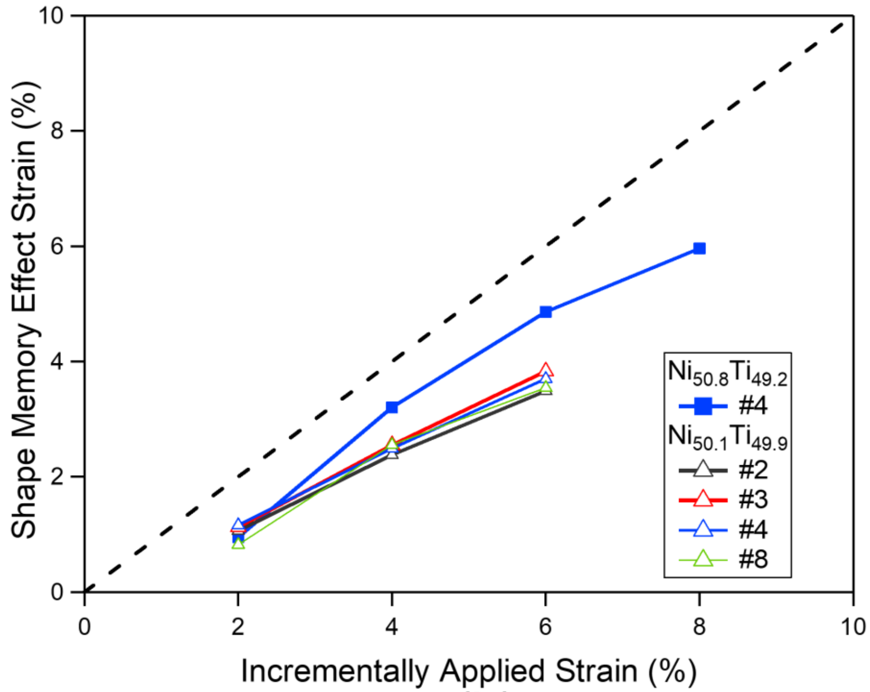


Tensile ductility up to ~16% was achieved.

Shape Recovery Tests



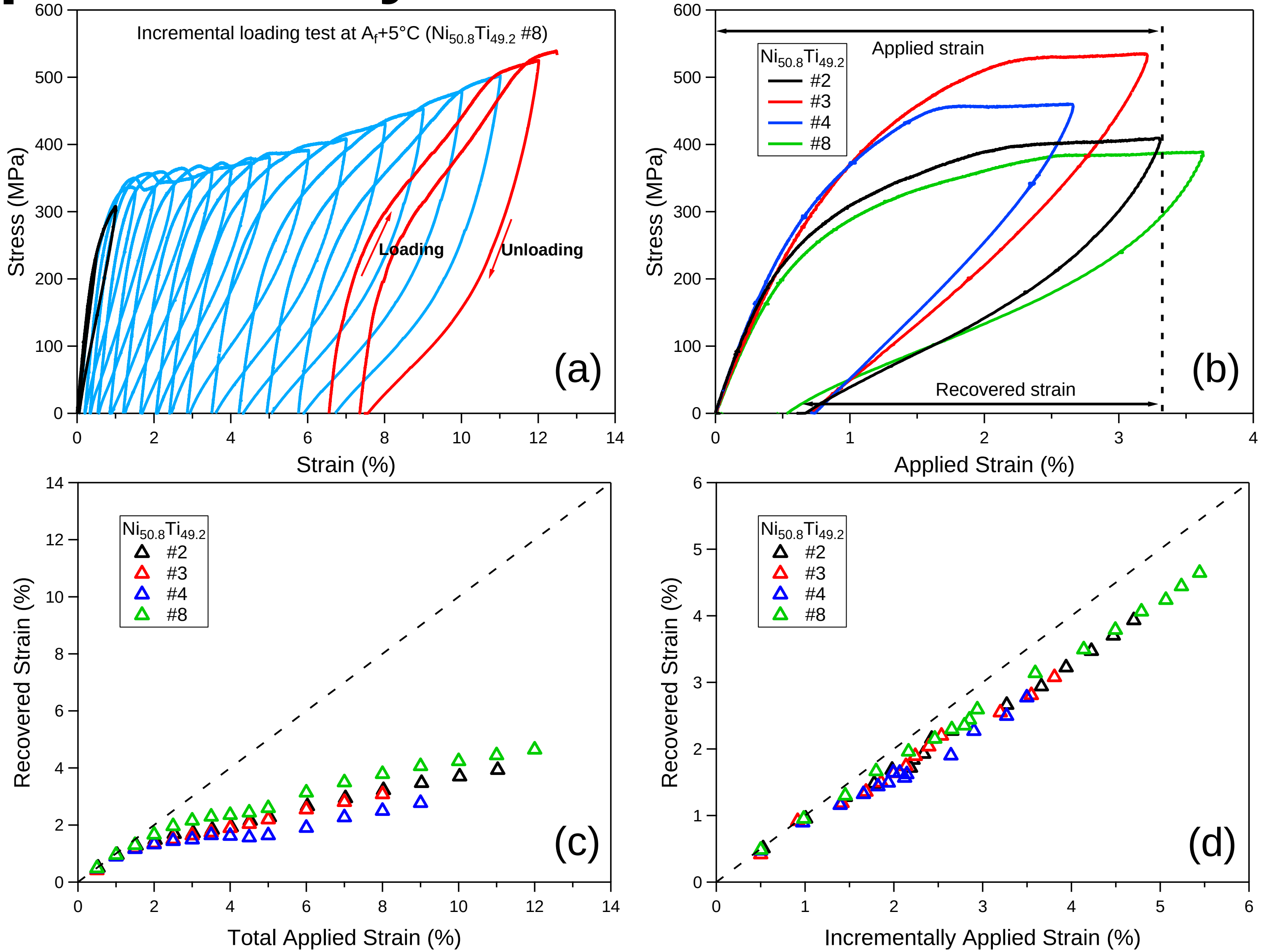
(a)



(b)

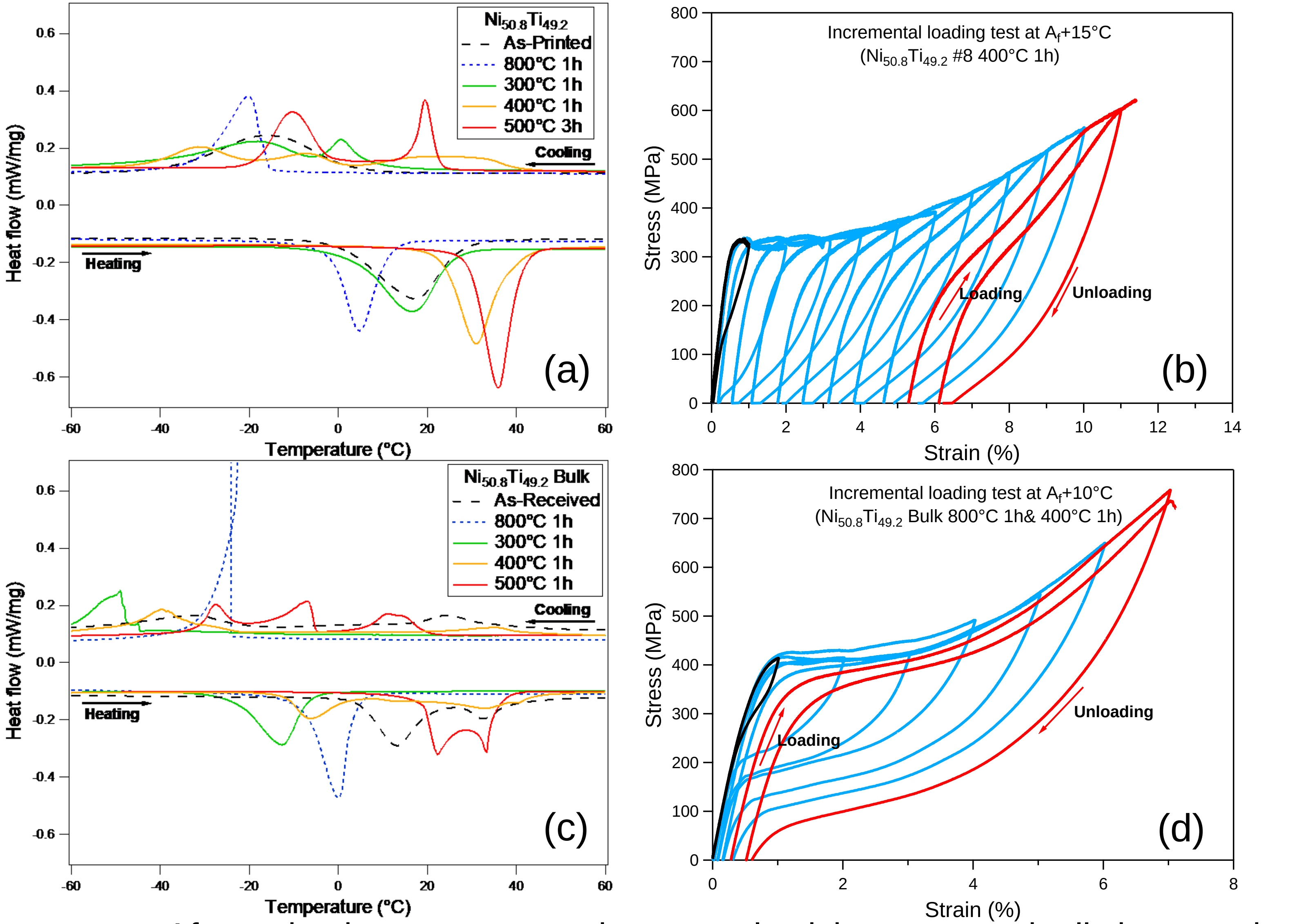
Tensile shape memory strain up to 6%

Superelasticity Tests



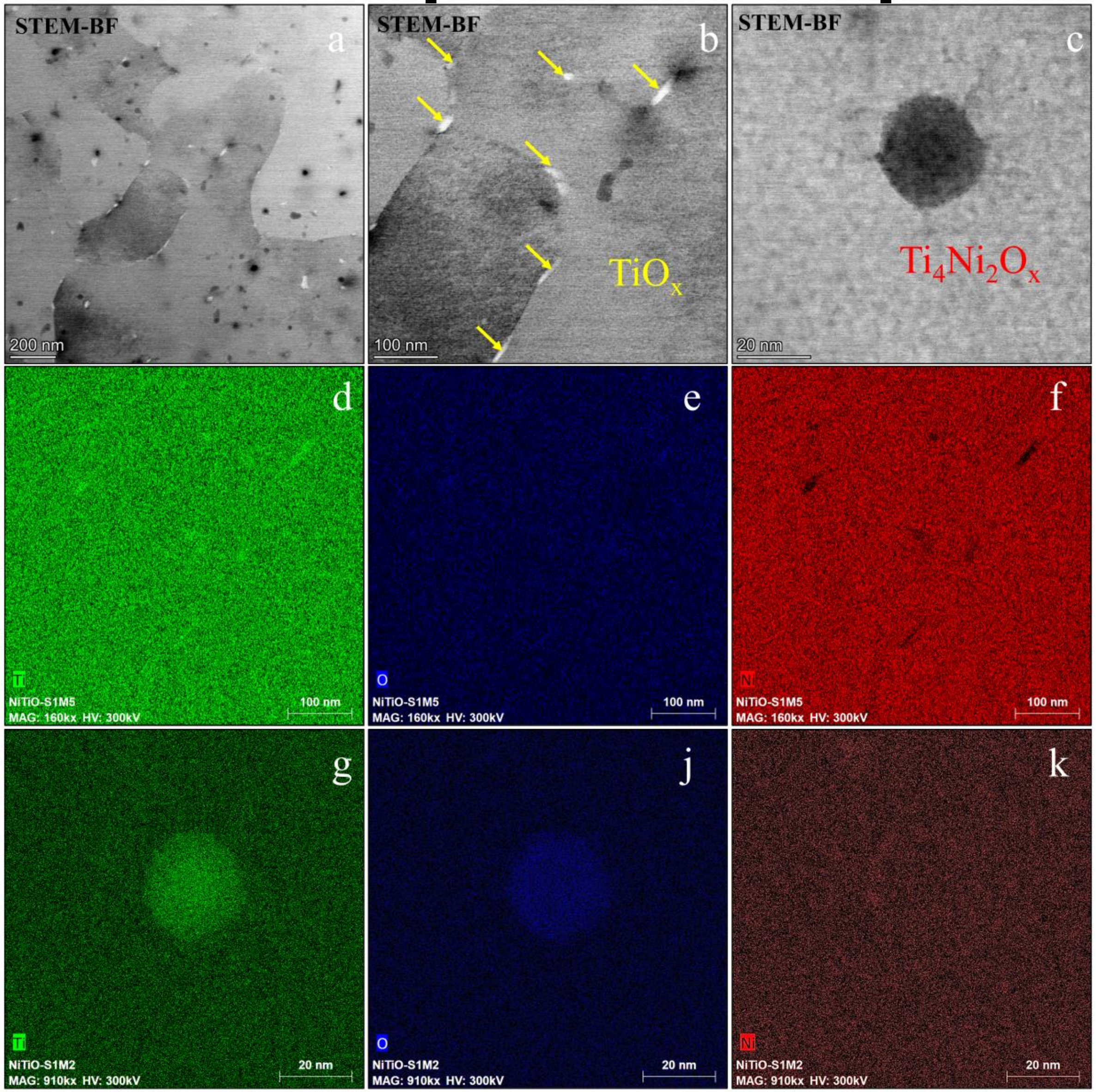
Partial superelasticity was observed in the as-printed NiTi.

Aging and Superelasticity



After aging heat treatment, the superelasticity was marginally improved.

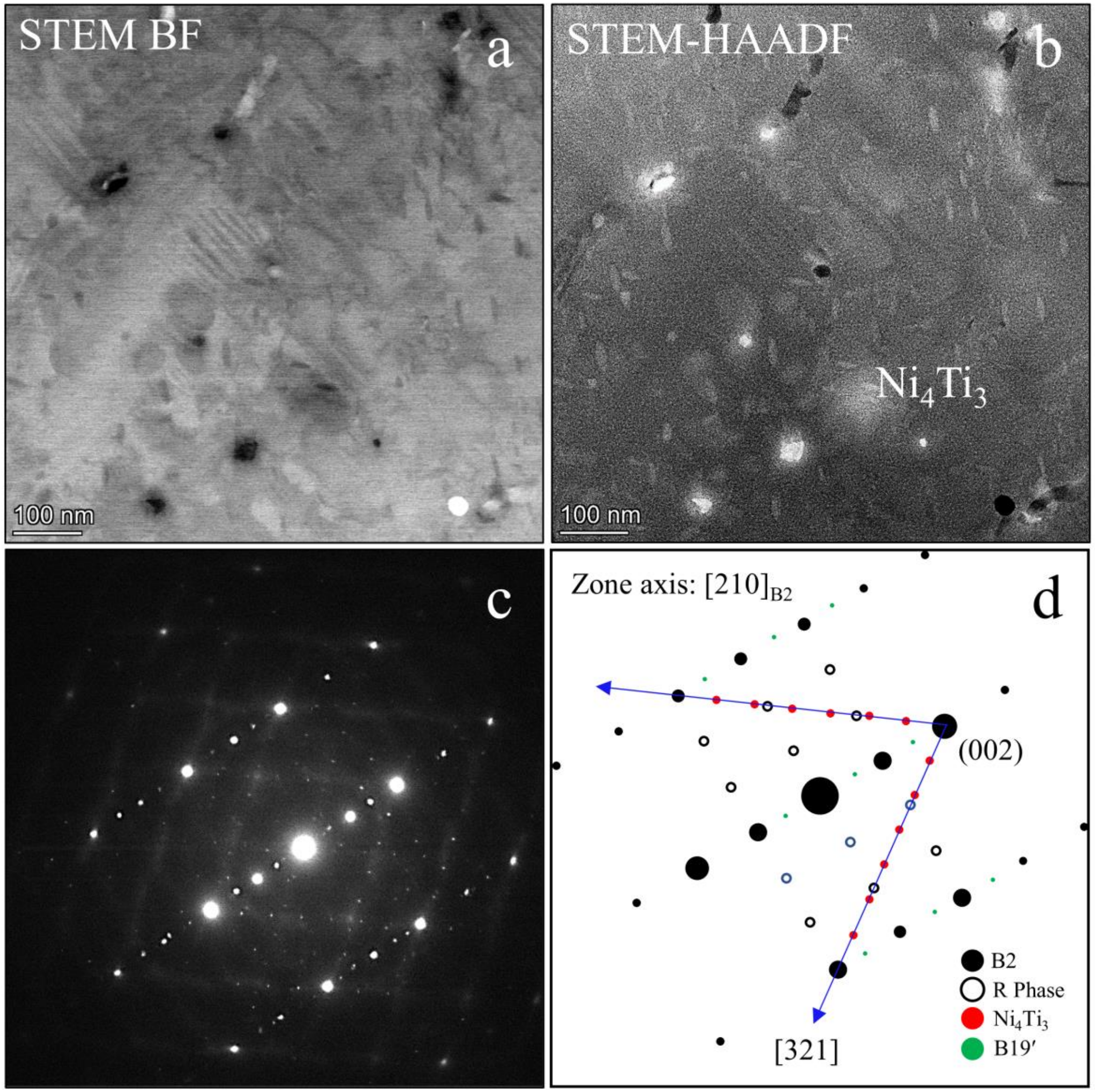
TEM of As-printed Sample



No Ni_4Ti_3 precipitates were observed as-printed sample.

Ti-rich oxides were observed.

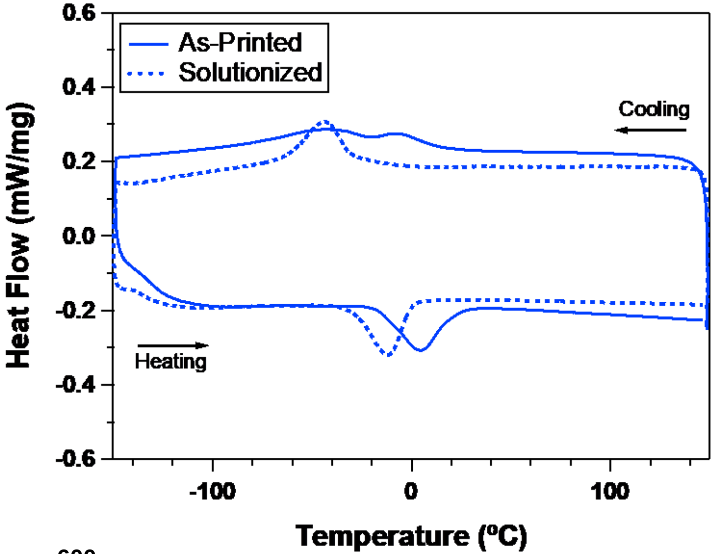
TEM of Aged Sample

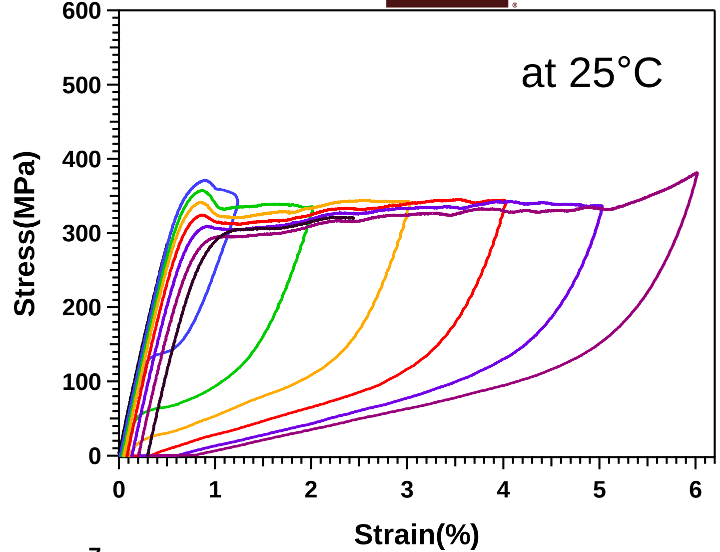


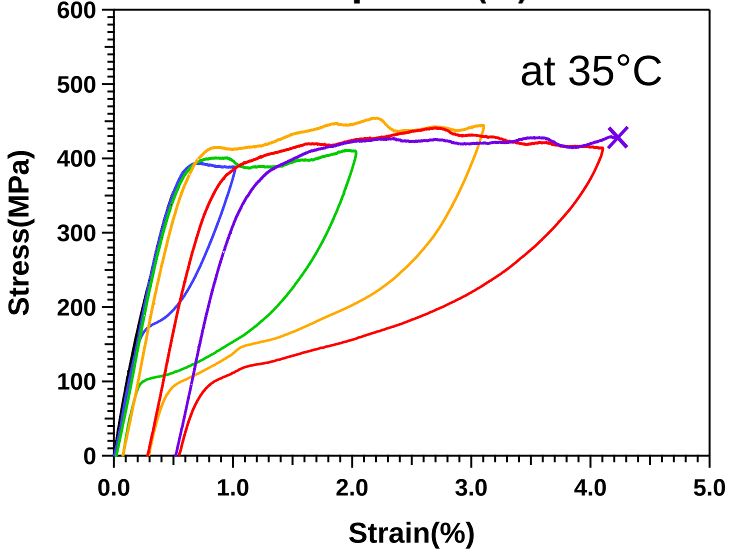
Ni_4Ti_3 precipitates were observed in the aged (400°C 1h) NiTi sample fabricated through SLM.

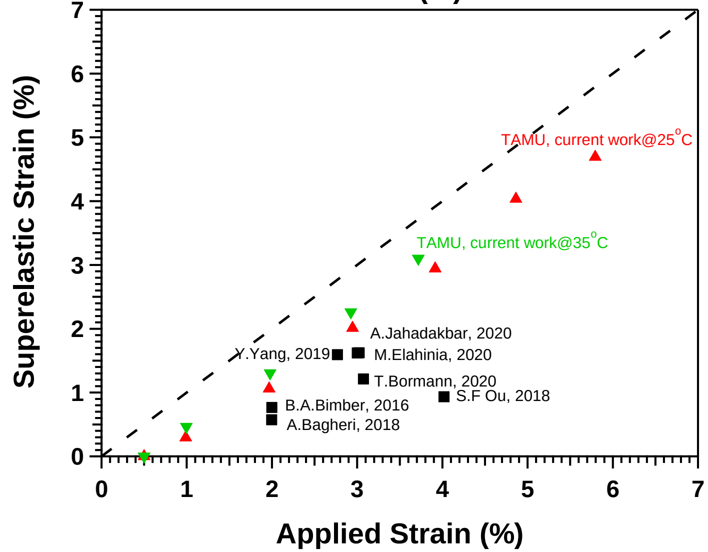
But the volume fraction seems low, and this might be reason why perfect superelasticity was not achieved.

Superelasticity from a Ni-richer NiTi Powder









In our very recent work on a Ni-Richer Powder, tensile superelastic train was able to reach 6%.

Conclusions

- Defect free NiTi SMA parts can be fabricated through SLM.
- Functional properties of AM NiTi are sensitive to Ni at.% and volumetric energy density (VED).
- Good ductility, shape momery effect, and superelasticity were achieved in AM NiTi.
- Improved thermal model is needed to predict the melt pool dimensions more accurately.

Thank You!

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For More Information:

L. Xue, K.C. Atli, S. Picak, C. Zhang, B. Zhang, A. Elwany, R. Arroyave, I. Karaman, "Controlling Martensitic Transformation Characteristics in Defect-Free NiTi Shape Memory Alloys Fabricated Using Laser Powder Bed Fusion and a Process Optimization Framework " *Acta Materialia – Under Review – 2021*

L. Xue, C. Zhang, K.C. Atli, A. Leff, A. Srivastava, N. Hite, D. Sharar, A. Elwany, R. Arroyave, I. Karaman, "Selective Laser Melting of Defect-Free NiTi SMA Parts with Superior Tensile Superelasticity" – in preparation – 2021

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I am currently looking for a job in industry. Email: leixue11@tamu.edu