SAND2017-7598C

Orientation Effects on Fatigue Behavior of Additively Manufactured Stainless Steel

Thale R. Smith[1], Joshua D. Sugar[2], Chris San Marchi[2], and Julie M. Schoenung[3]

[1]University of California Davis, [2]Sandia National Laboratories, [3]University of California Irvine

Acknowledgments

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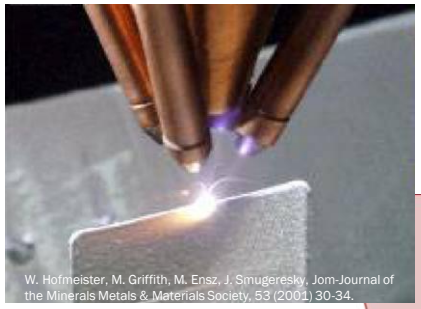
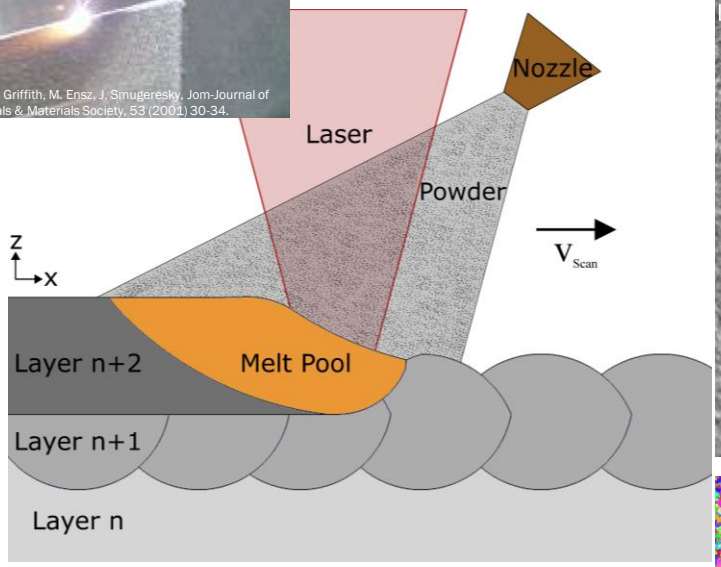
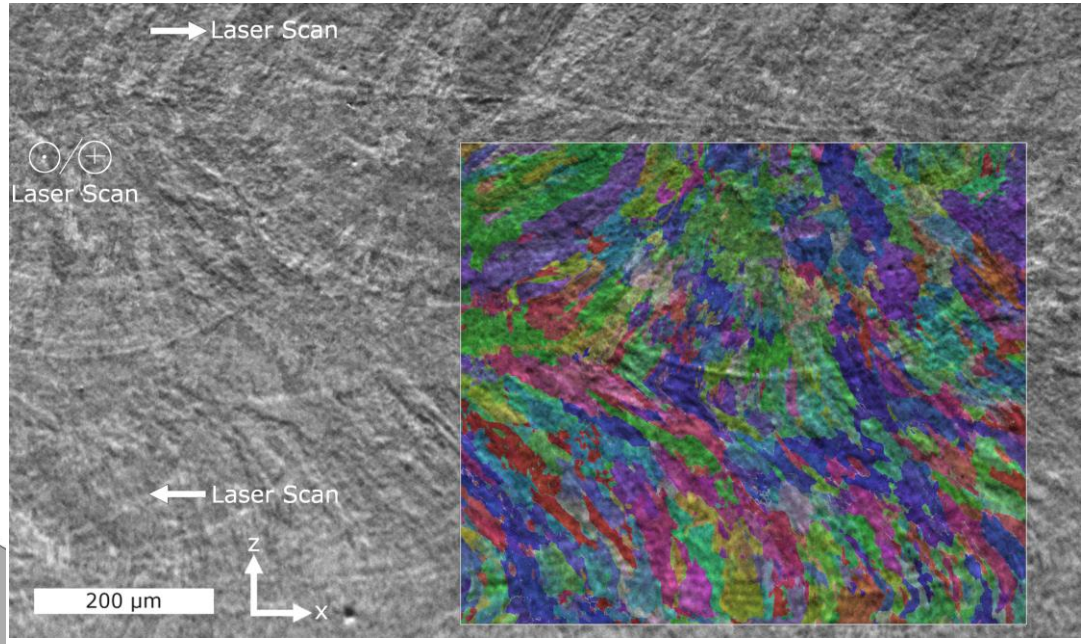
Direct Energy Deposition (DED)





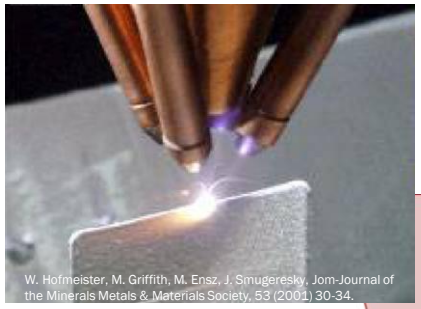
DED 304L

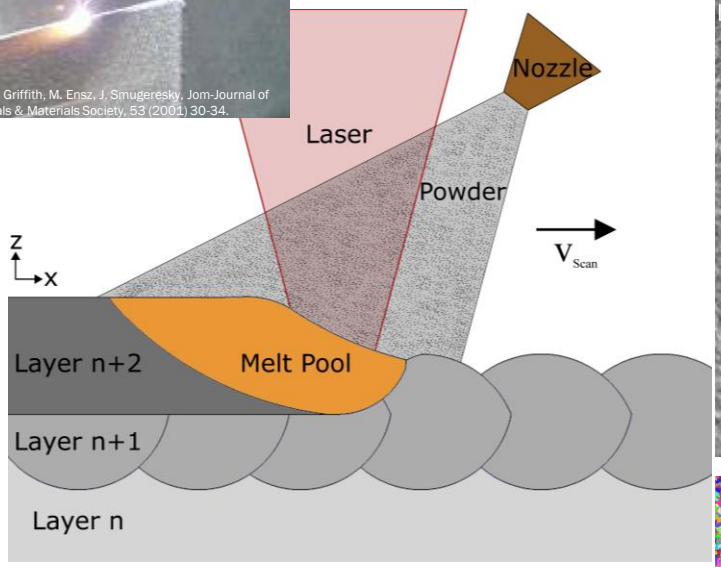


- **Fusion zone solidification**
- Cyclic heating/cooling
- Difficult to control properties in complex geometries

308L/304L Weld

Direct Energy Deposition (DED)





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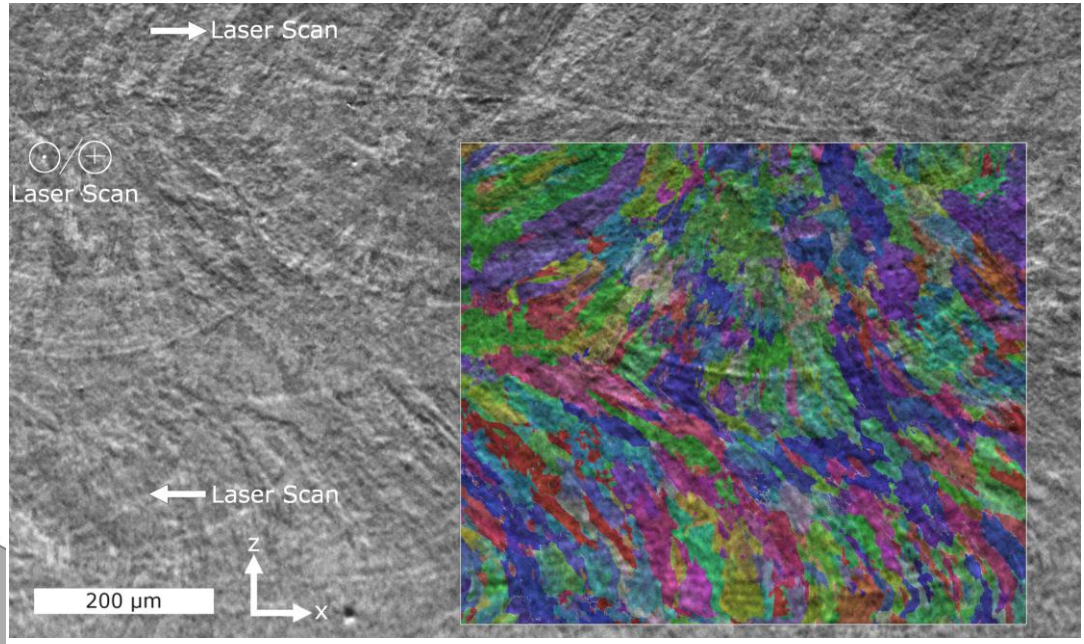
DED 304L



308L/304L Weld

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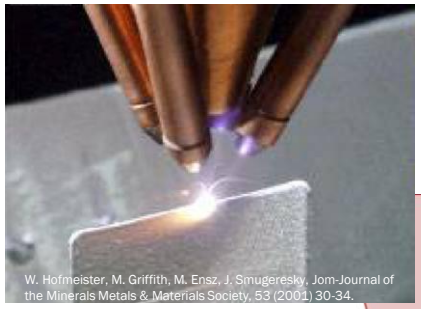
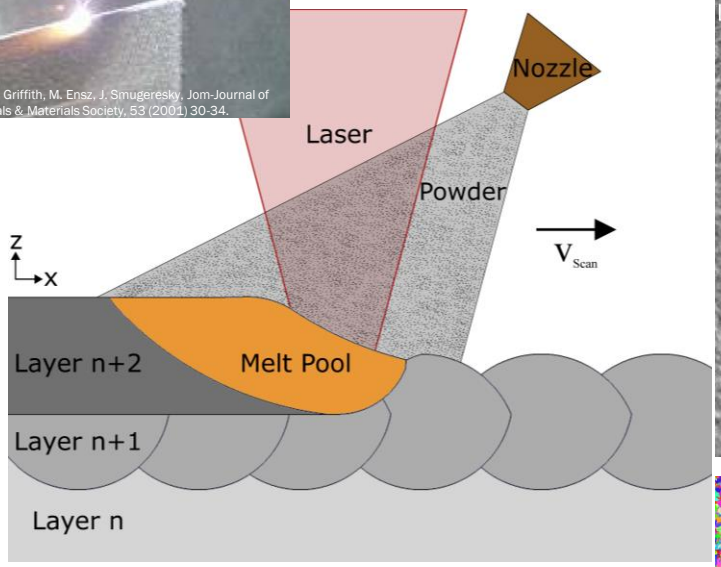
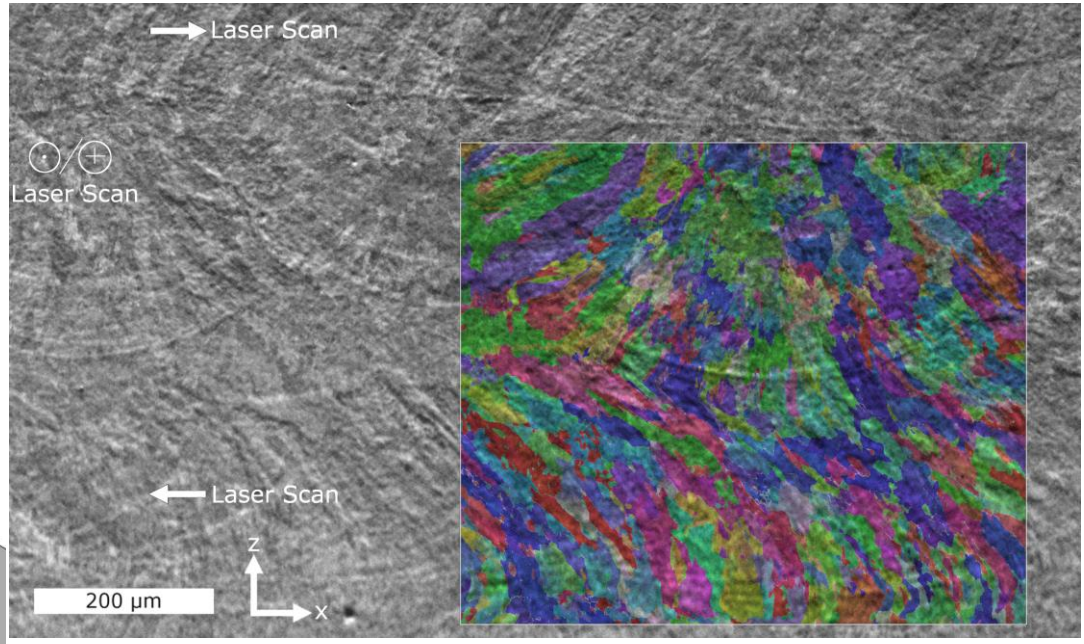




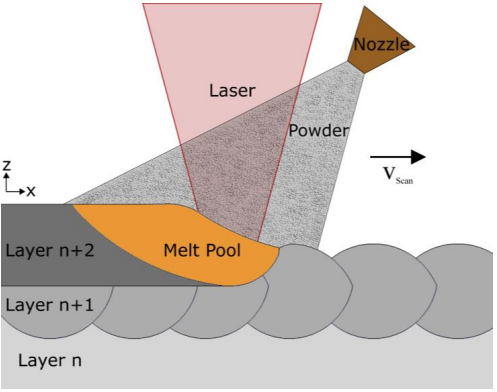
DED 304L

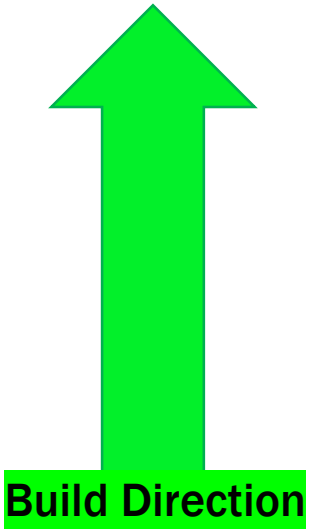


308L/304L Weld

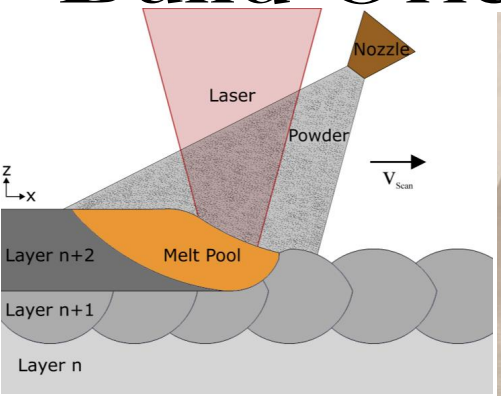
- Fusion zone solidification
- Cyclic heating/cooling
- **Difficult to control properties in complex geometries**

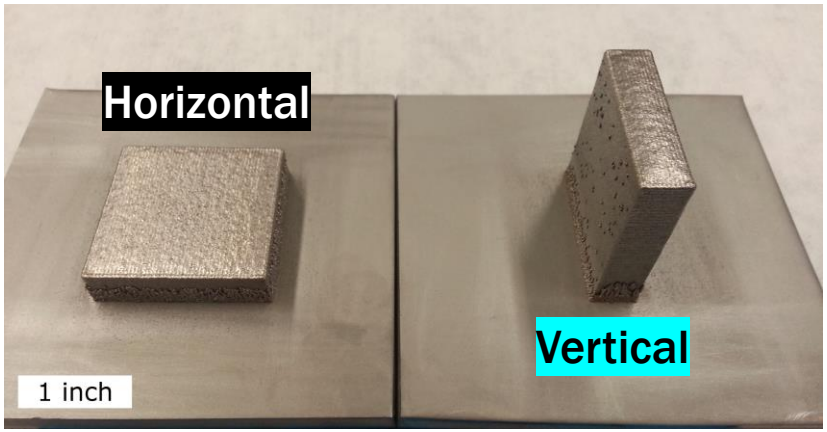
DED Orientation Effects

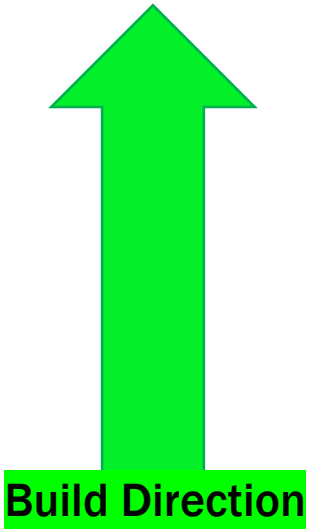




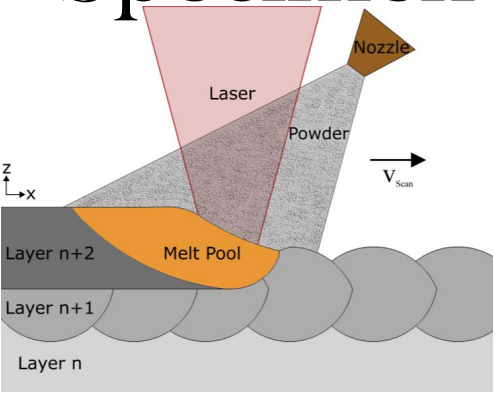
Build Orientation

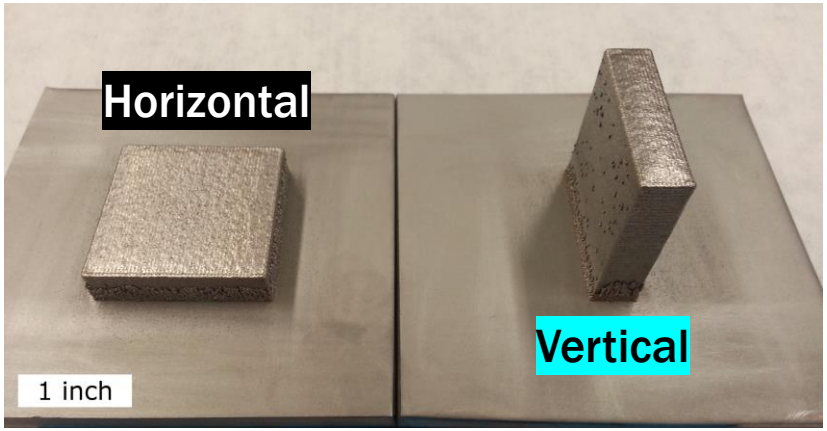


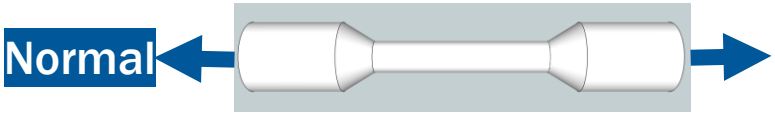


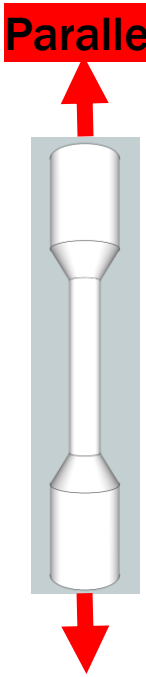


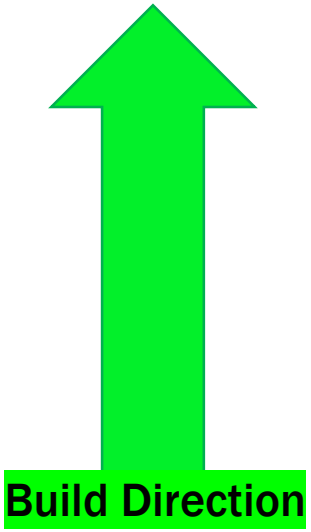
Specimen Orientation



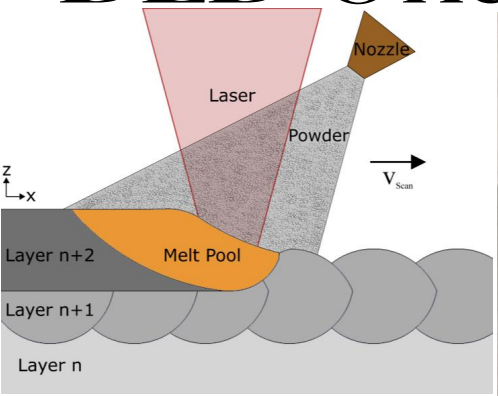


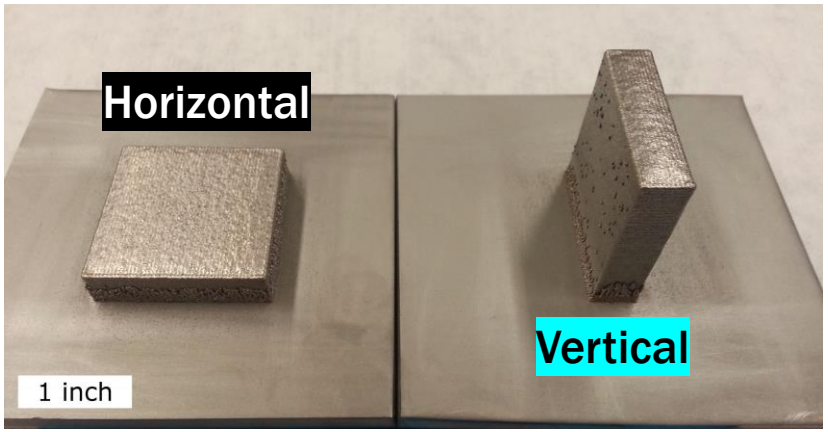


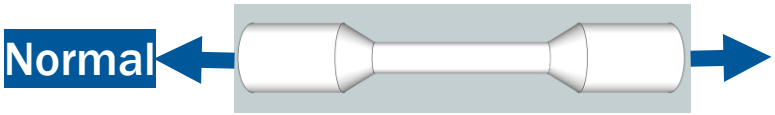


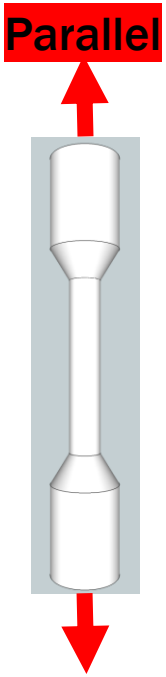


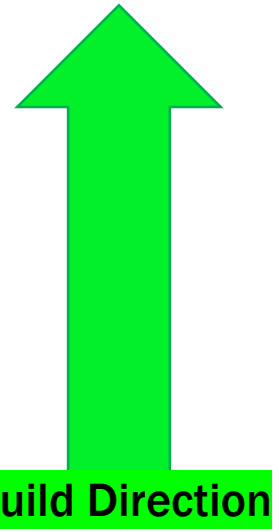
DED Orientation Effects











Author	Grade	Yield Strength Horizontal-Normal (MPa)	Yield Strength Vertical-Parallel (MPa)	Percent Difference (%)
Griffith et al.	304L	448	324	32
	316L	593	448	28
Smugeresky et al.	304L	503	407	21
Yu et al.	316L	495	275	57
Zhang et al.	316L	558	352	45

M.L. Griffith, M.T. Ensz, J.D. Puskar, C.V. Robino, J.A. Brooks, J.A. Philliber, J.E. Smugeresky, W.H. Hofmeister, MRS Online Proceedings Library, 625 (2000).
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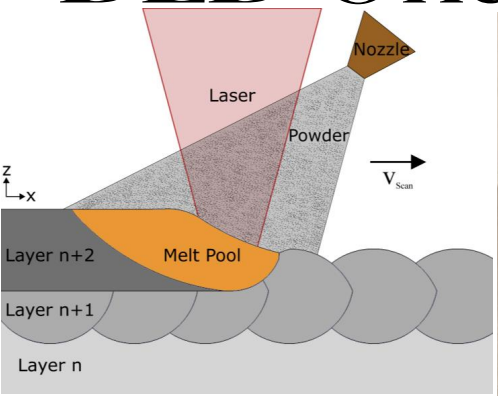
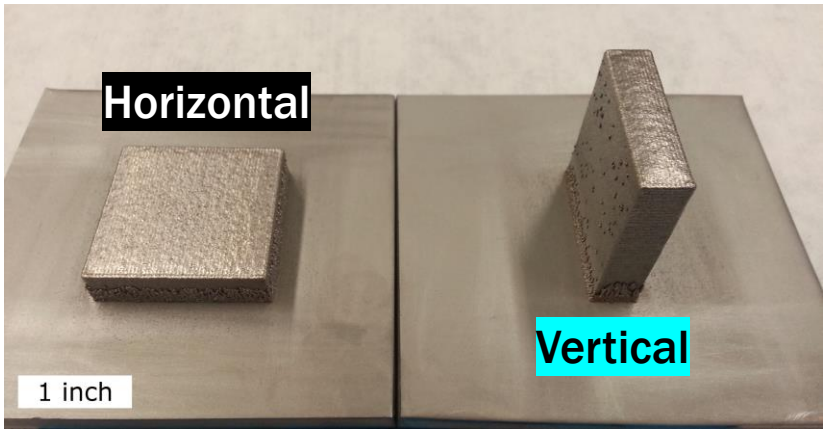
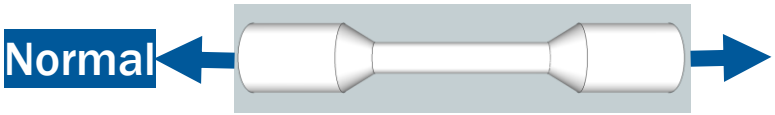
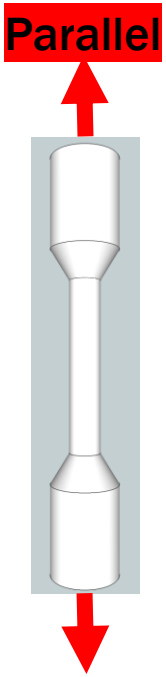
K. Zhang, S. Wang, W. Liu, X. Shang, Materials & Design, 55 (2014) 104-119.;

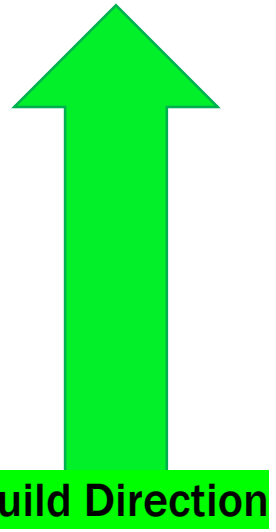
DED Orientation Effects











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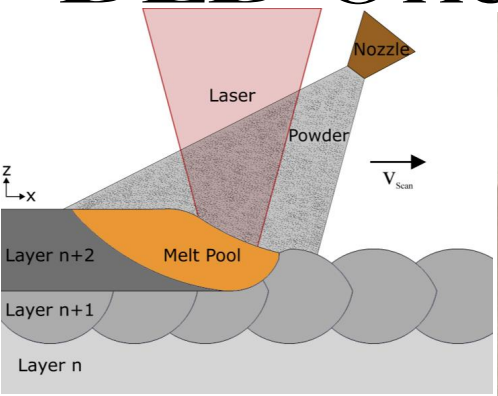

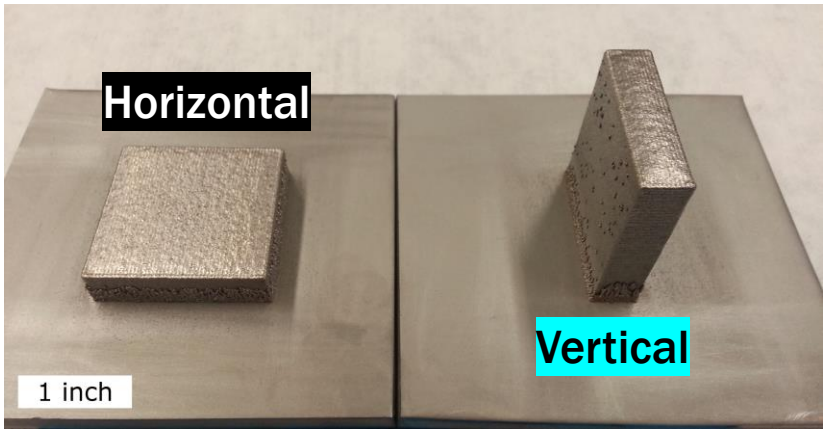

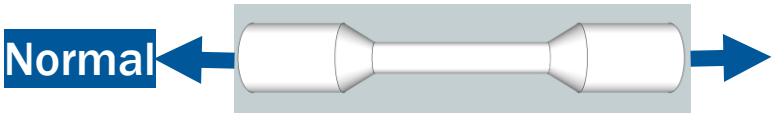

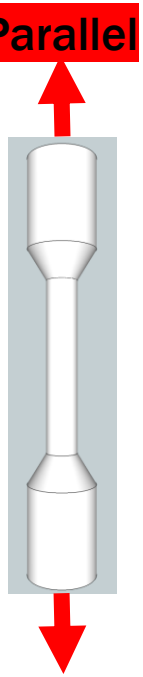

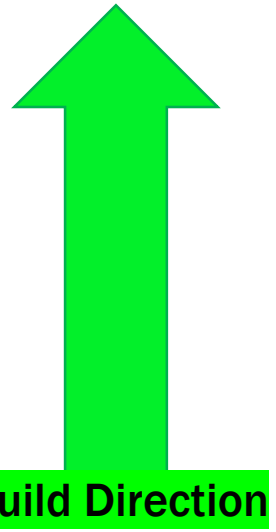

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What causes orientation effects?

What is effect of build orientation on fatigue behavior?

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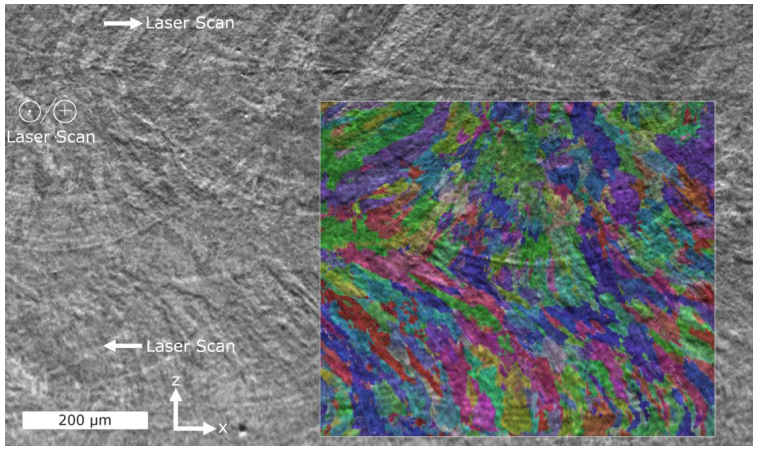
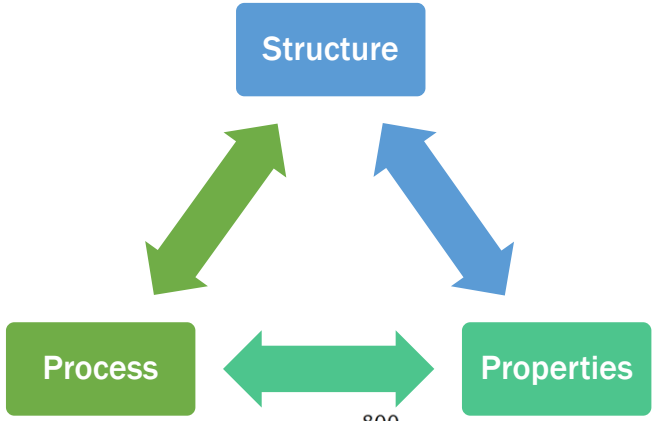
Goals

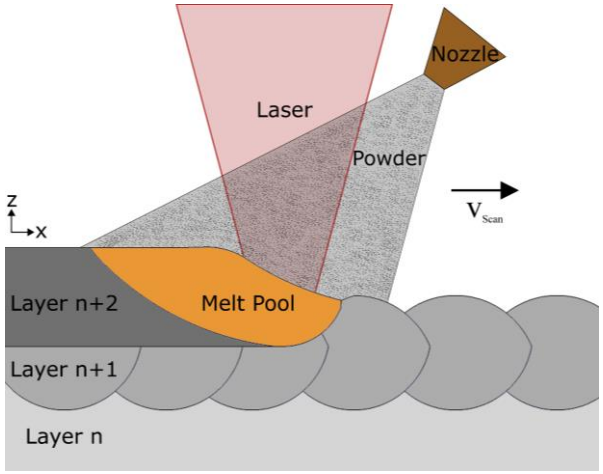
- Evaluate orientation effects
  - Tensile behavior
  - Fatigue behavior
  - Compare DED to conventional materials

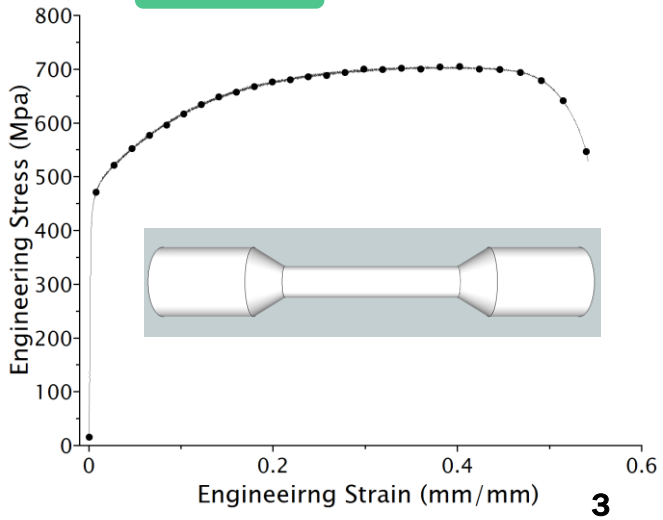


- What is relationship between orientation effects and defects?
  - Microstructural defects
  - Gross build defects



- Approach:
  - Tensile testing
  - Notched fatigue testing
  - Electron microscopy
  - Optical microscopy

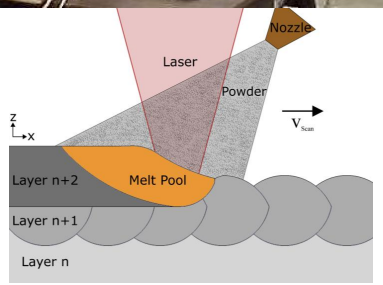




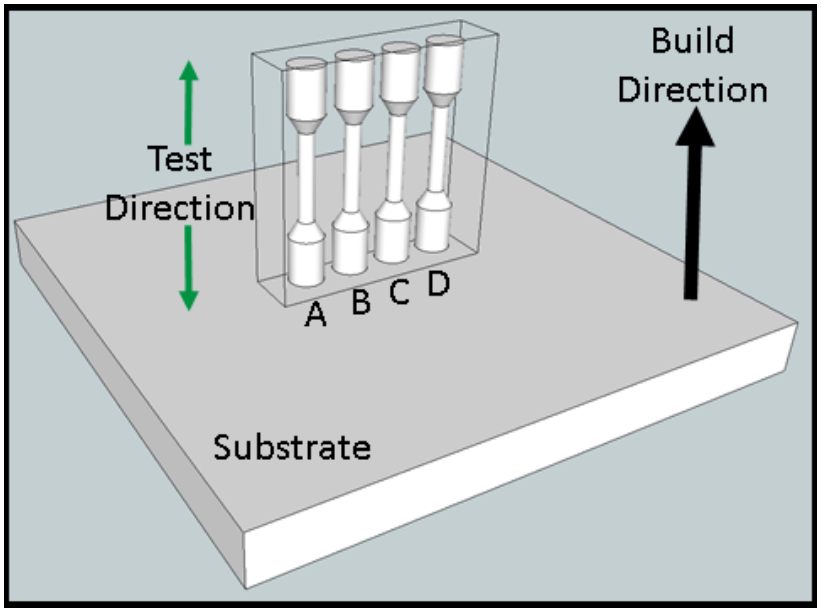
Tensile Build Approach

Tensile		
Parameter	Value	Unit
Laser	Nd:Yag	-
Laser Power	400	W
Scan speed	17	mm/s
Hatch increment	0.41	mm
Layer increment	0.25	mm
Hatch rotation	90	degrees
Powder feed rate	16	g/min
Oxygen	<15	ppm

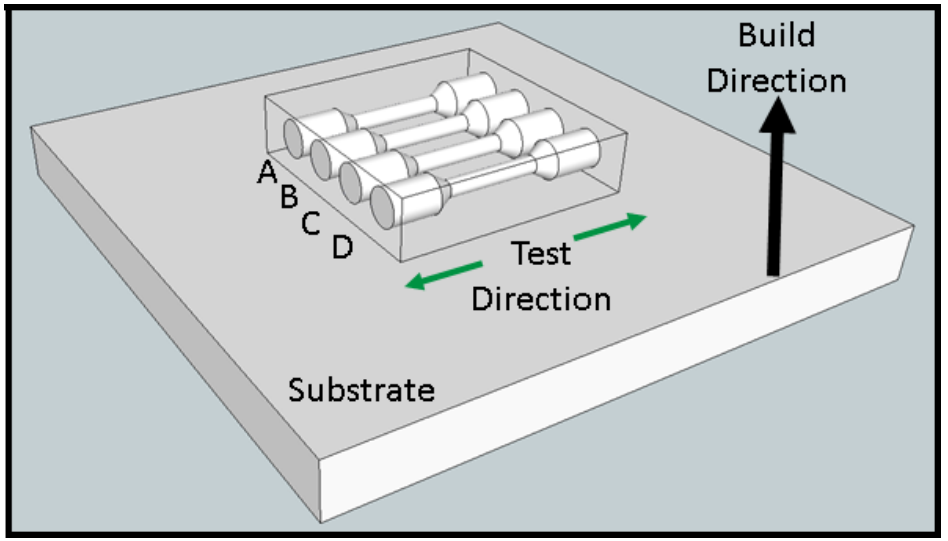
LENS 750 workstation



Vertical (V)



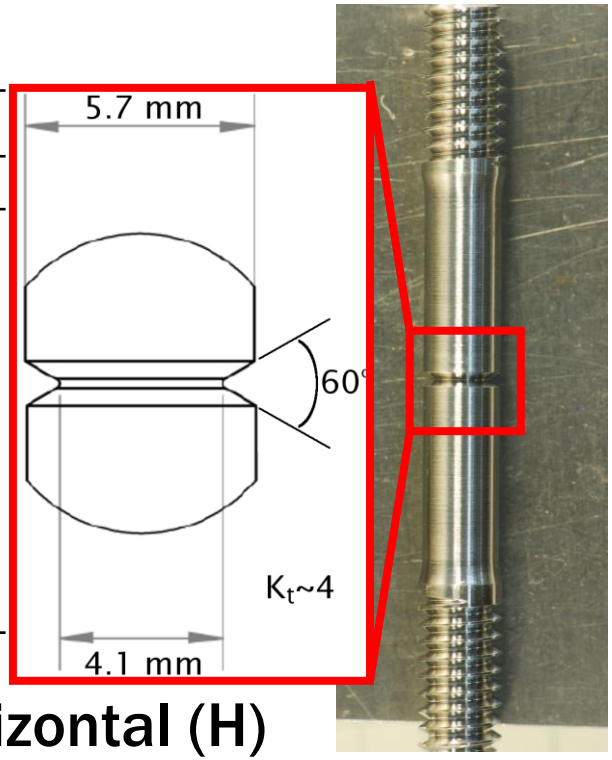
Horizontal (H)



Fatigue Build Approach

Tensile		
Parameter	Value	Unit
Laser	Nd:Yag	-
Laser Power	400	W
Scan speed	17	mm/s
Hatch increment	0.41	mm
Layer increment	0.25	mm
Hatch rotation	90	degrees
Powder feed rate	16	g/min
Oxygen	<15	ppm

Fatigue		
Parameter	Value	Unit
Laser	Yb:Fiber	-
Laser Power	400	W
Scan speed	11	mm/s
Hatch increment	0.46	mm
Layer increment	0.34	mm
Hatch rotation	90	degrees
Powder feed rate	34	g/min
Oxygen	<15	ppm



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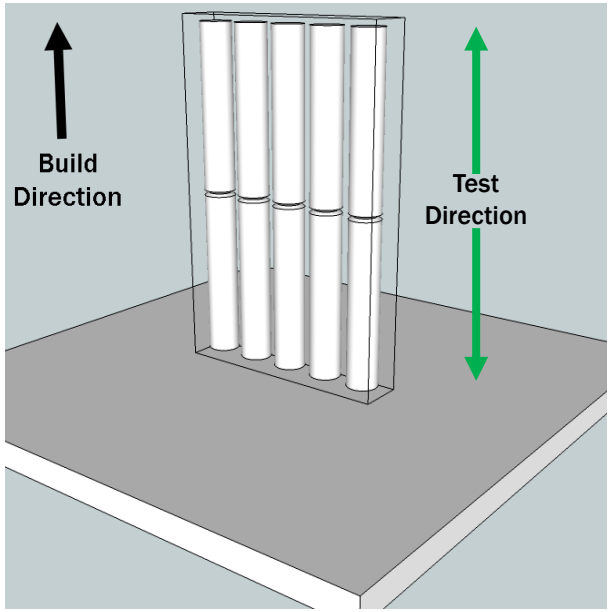
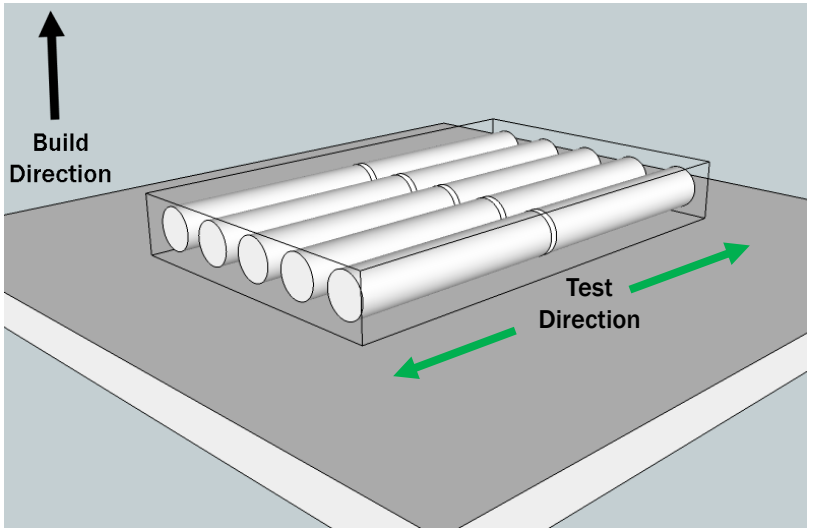
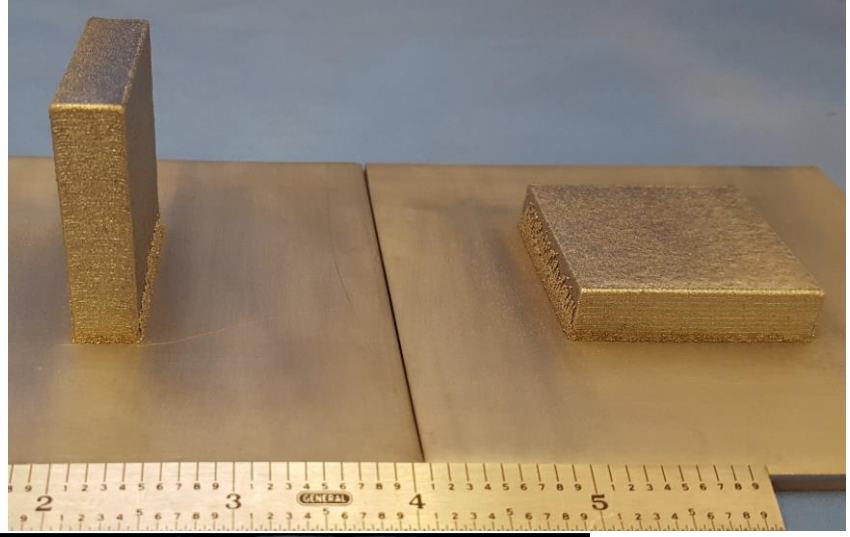


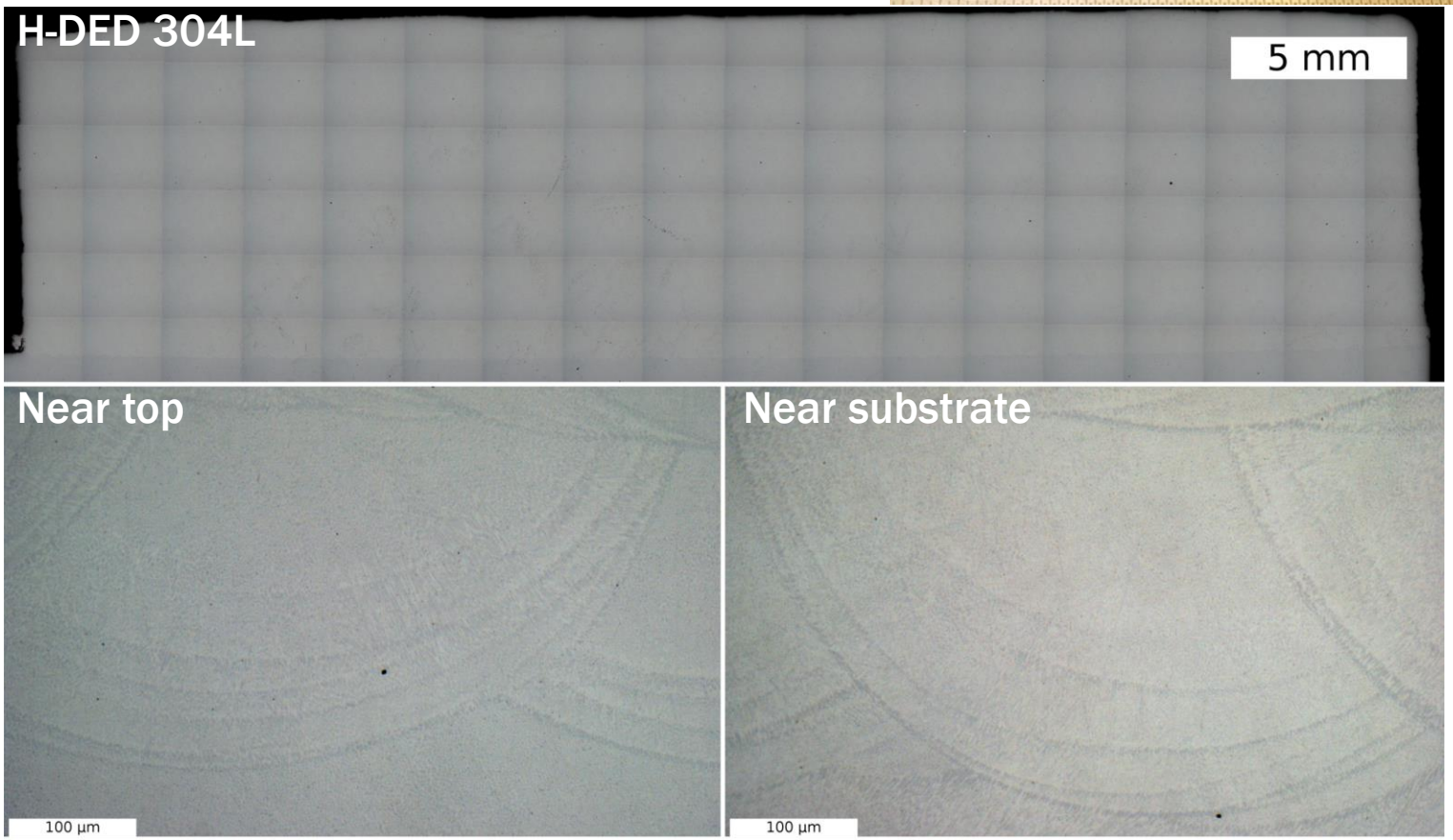
Horizontal (H)



Tensile Build Density

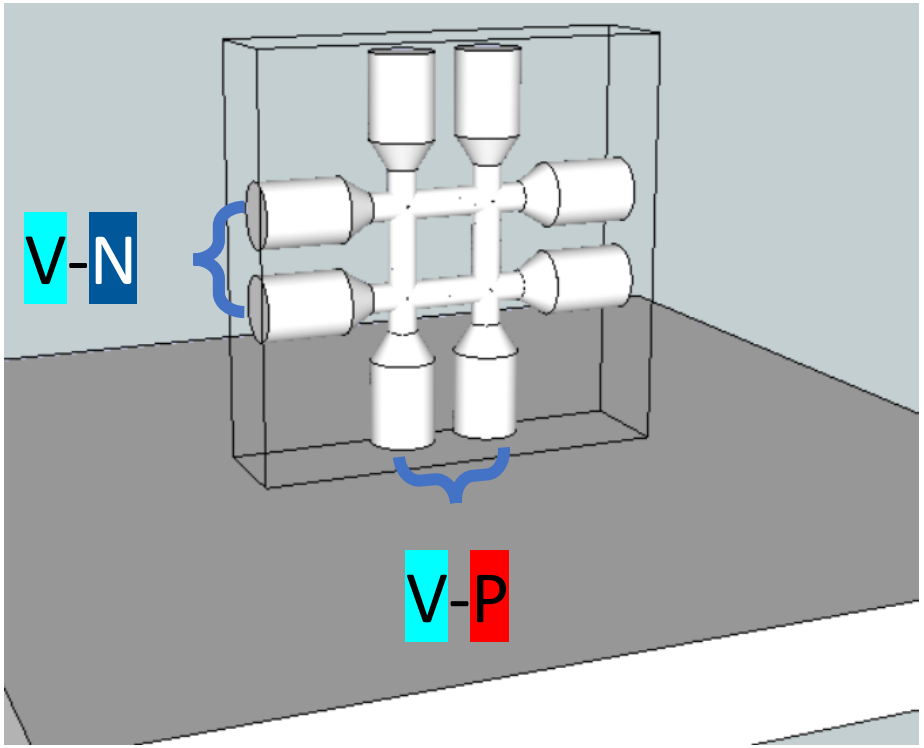
- Deposit density > 99% (Archimedes)
- No apparent gross defects
- Typical solidification structure



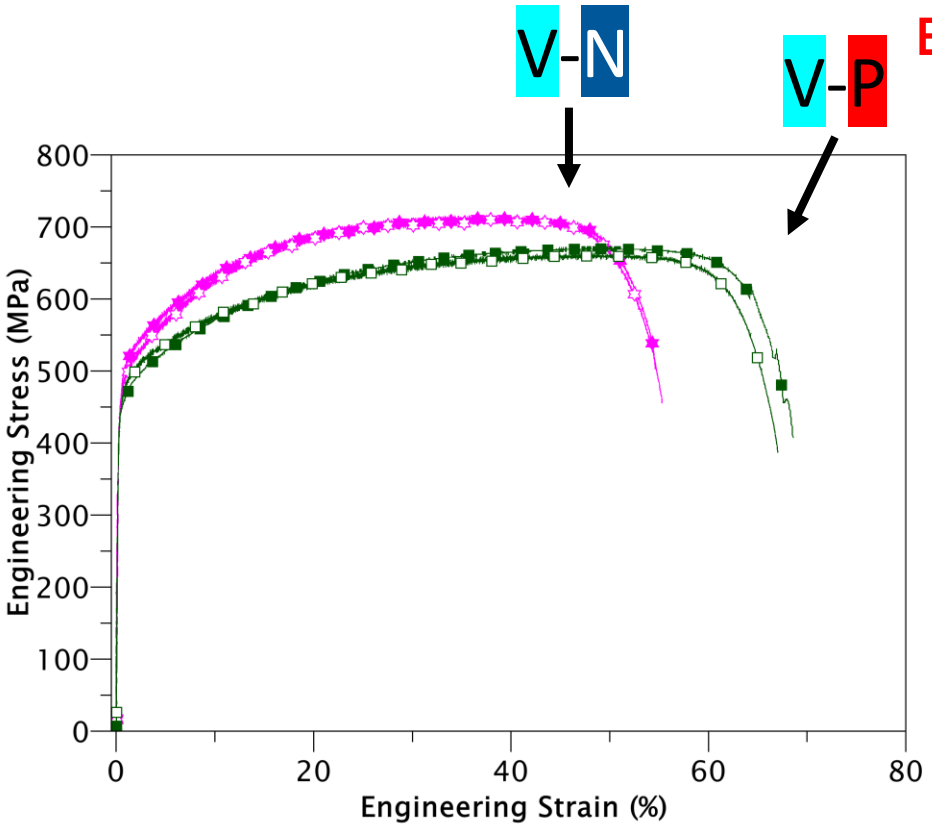


Specimen Orientation and Thermal History

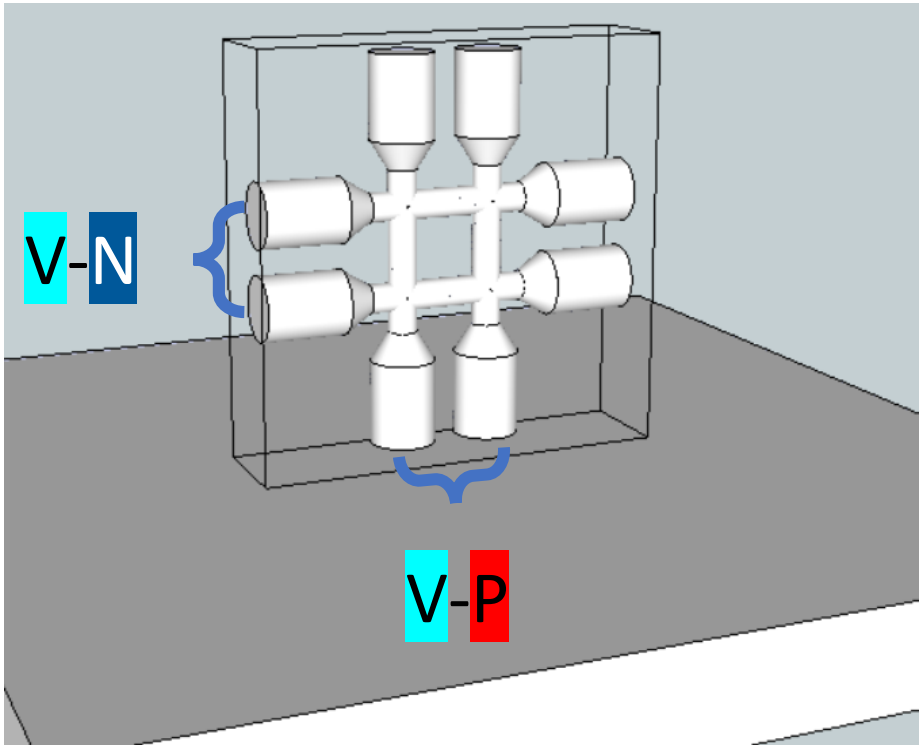
Build volume has similar thermal history



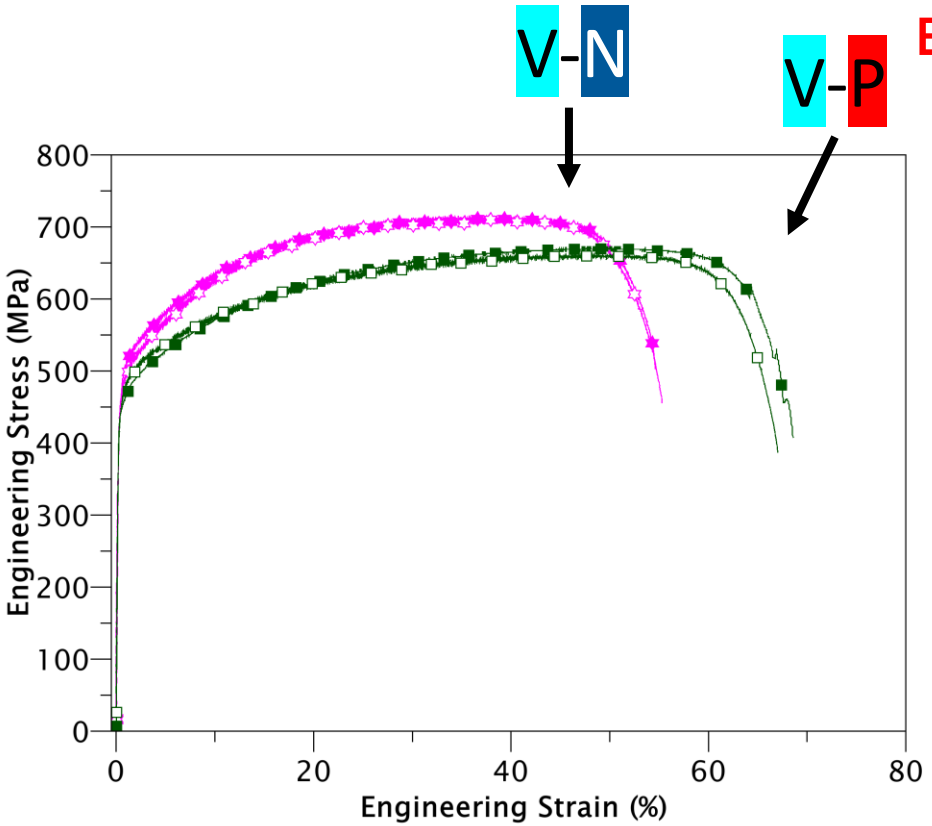
Specimen Orientation has Little Effect



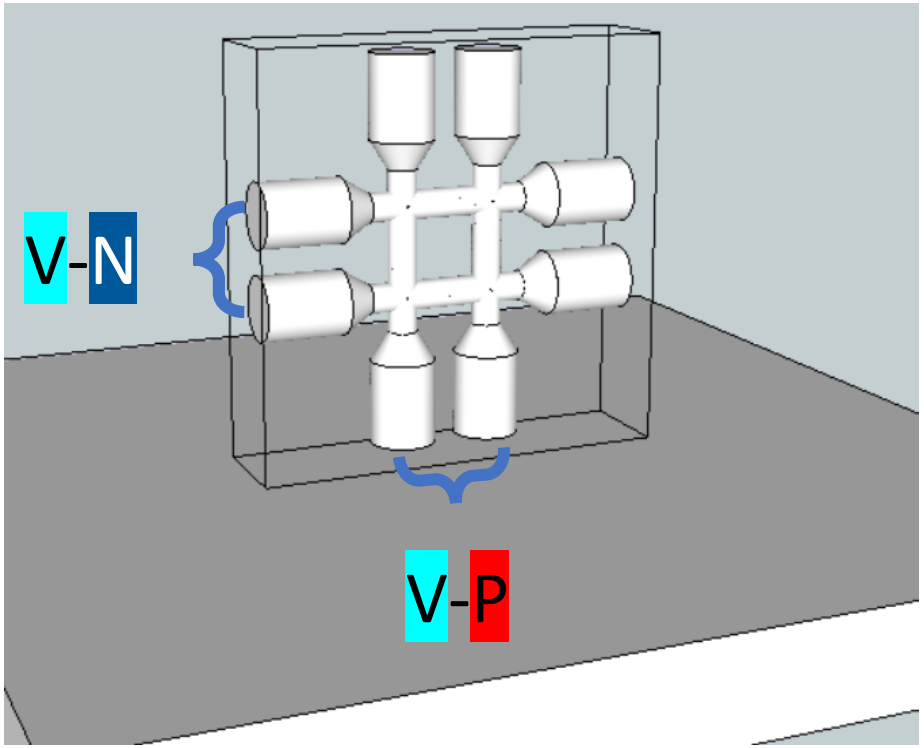
Build volume has similar thermal history



Specimen Orientation has Little Effect



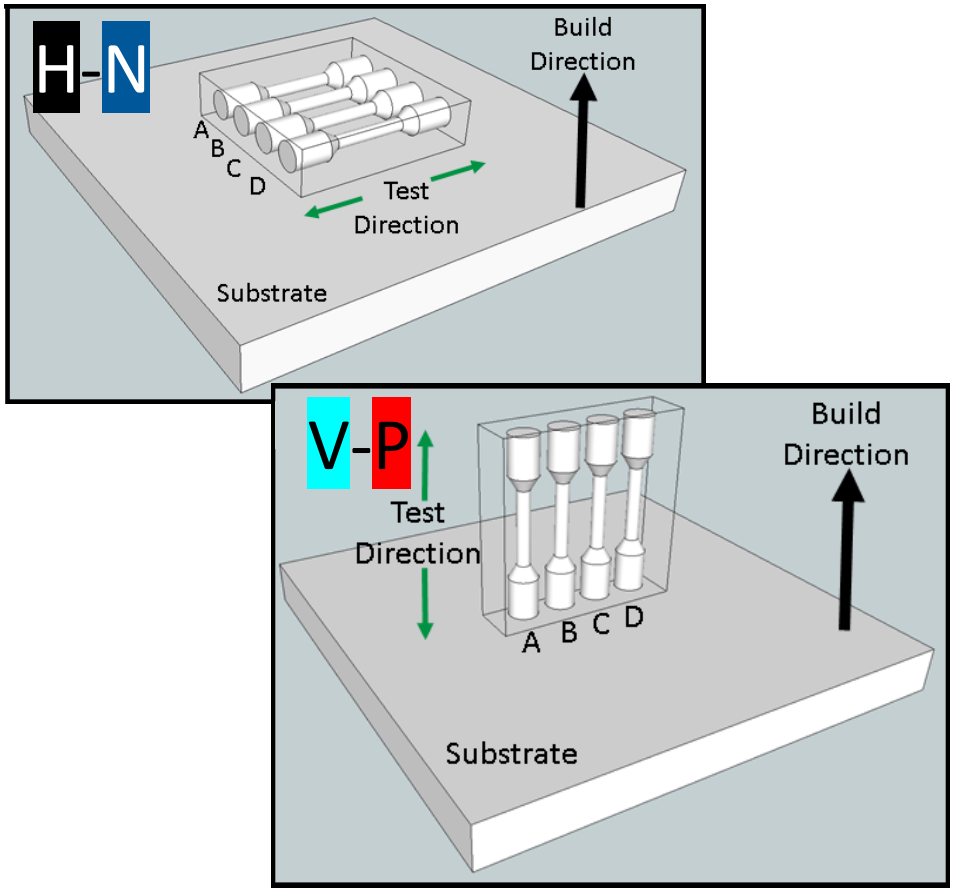
Build volume has similar thermal history



Author	Grade	Yield Strength Vertical-Normal (MPa)	Yield Strength Vertical-Parallel (MPa)	Percent Difference (%)
Present Study	304L	456	445	2

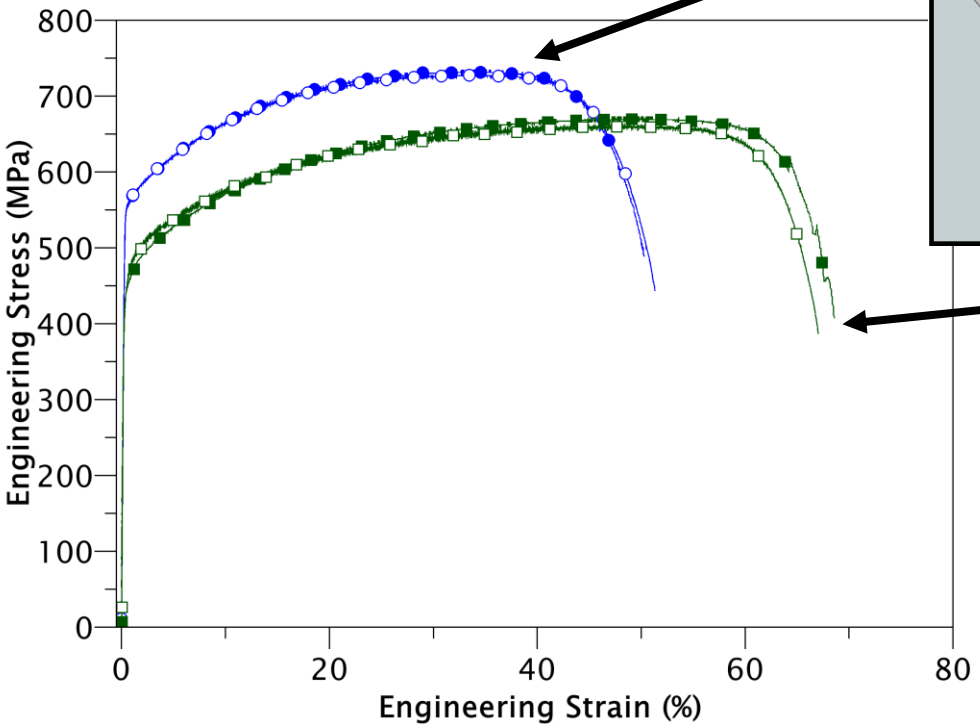
Build Orientation and Thermal History

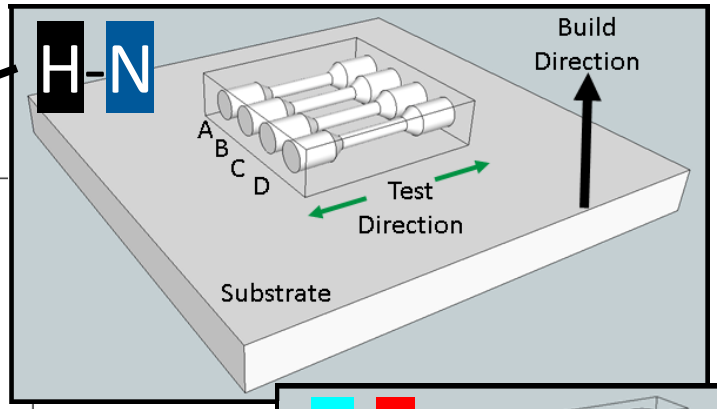
Builds experience different thermal histories

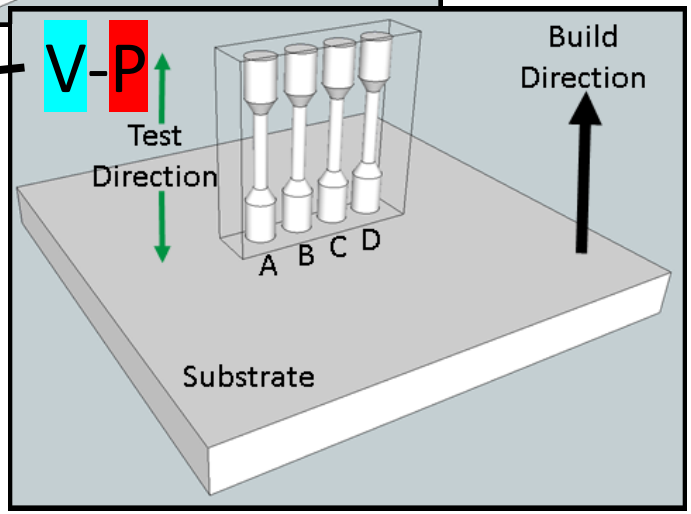


Build Orientation and Thermal History

Builds experience different thermal histories

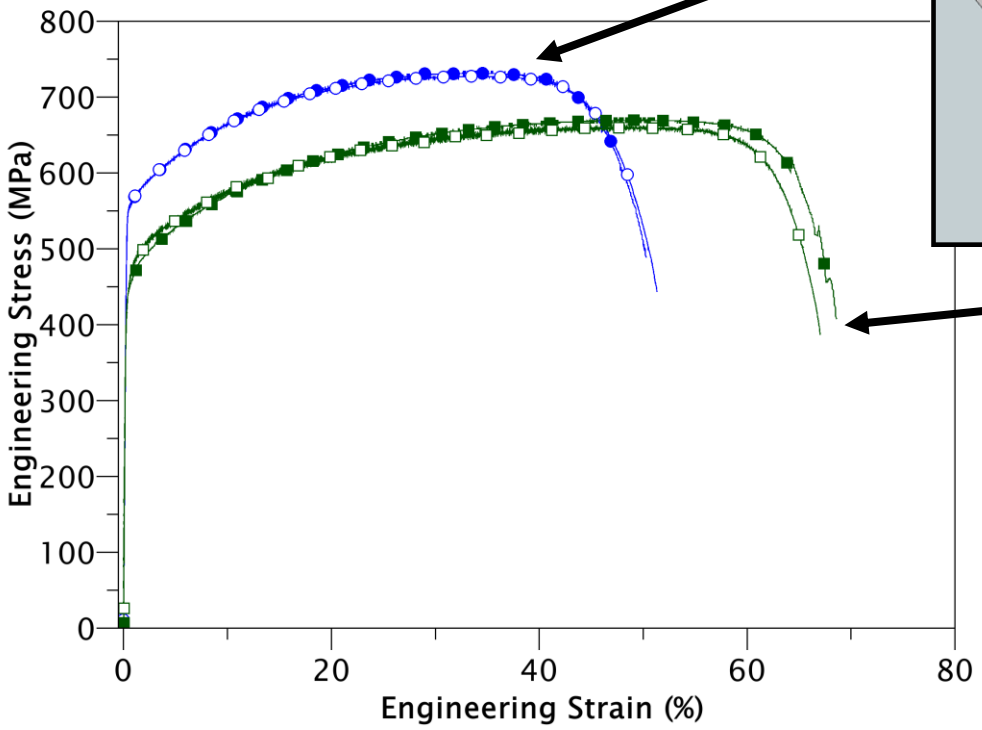


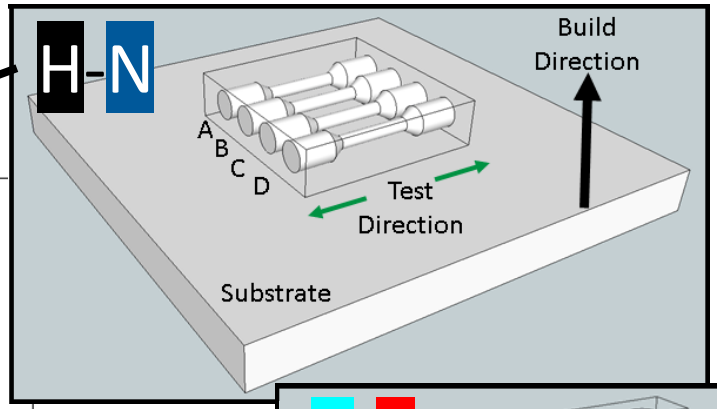


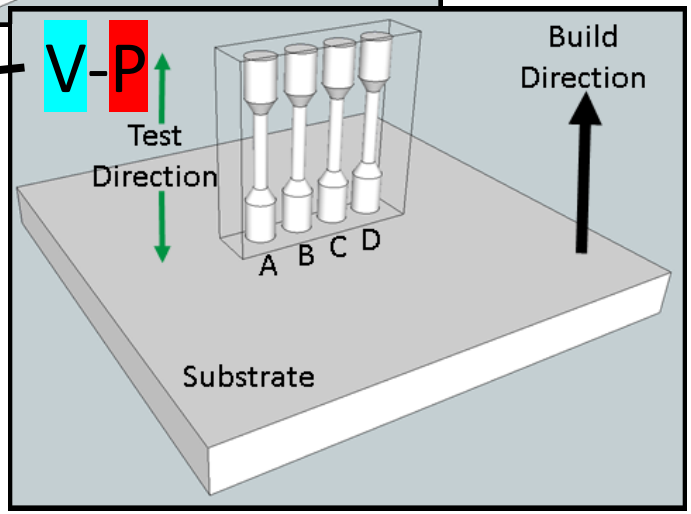


Build Orientation and Thermal History

Builds experience different thermal histories

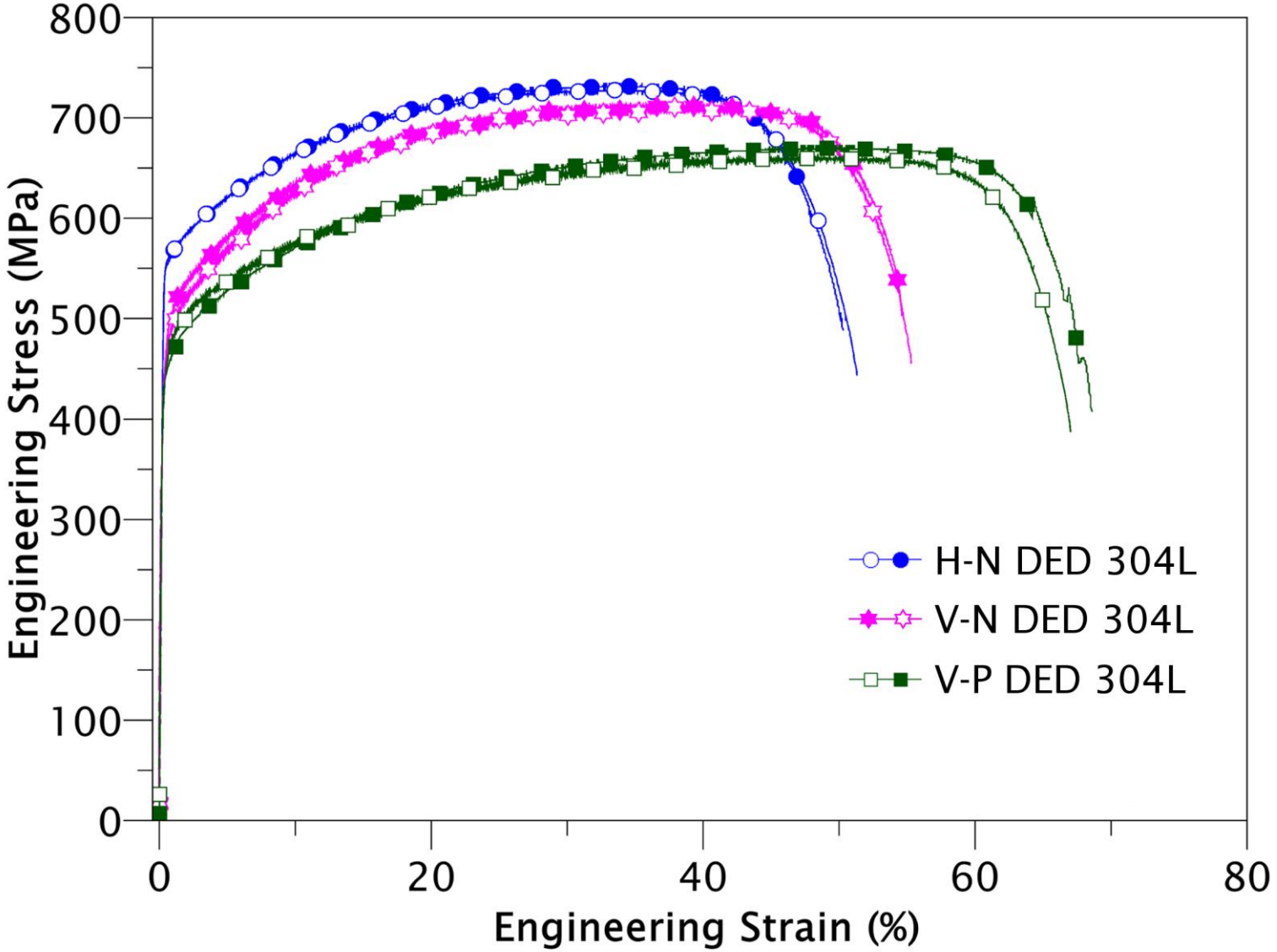




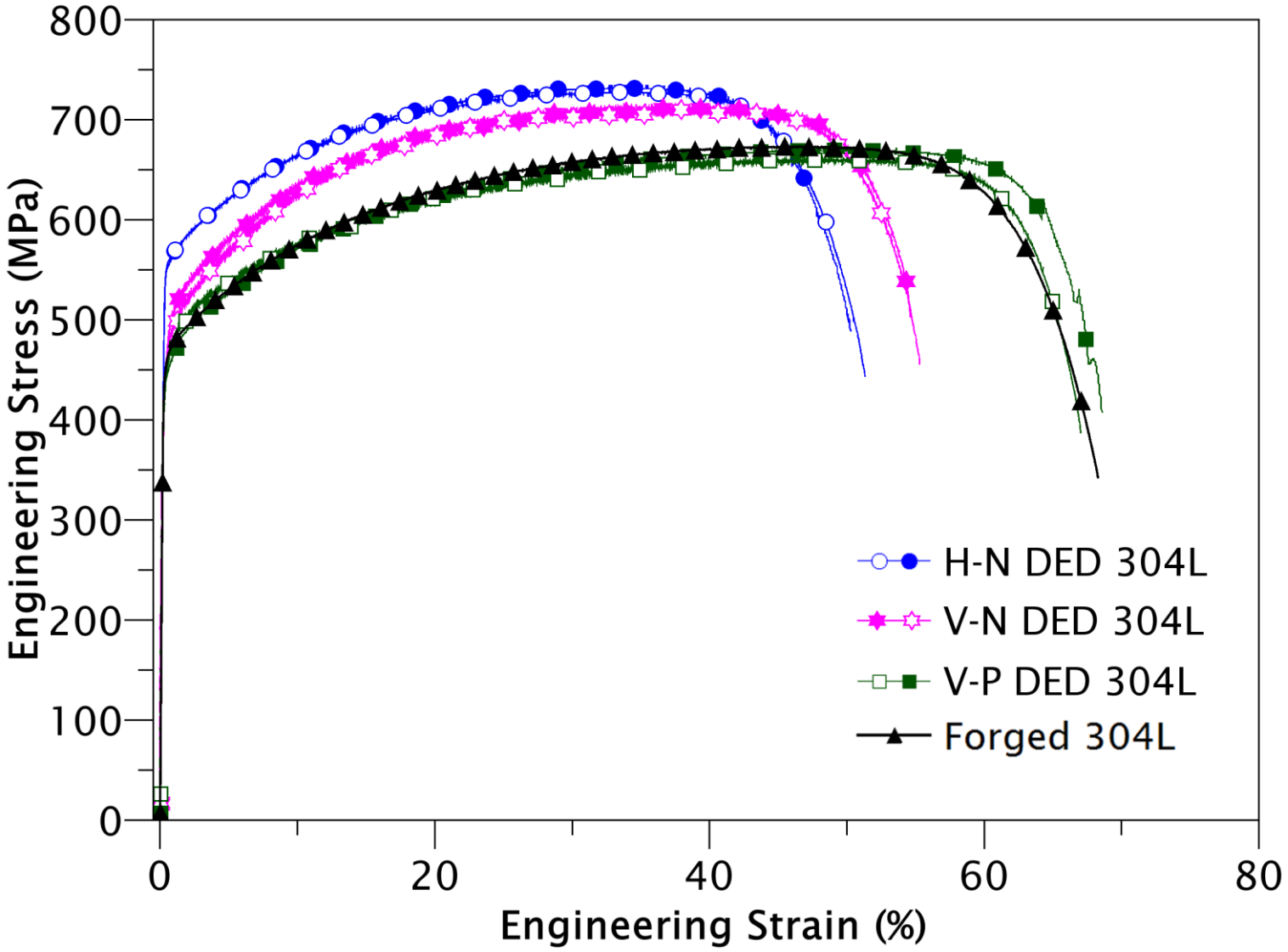


Author	Grade	Yield Strength Horizontal-Normal (MPa)	Yield Strength Vertical-Parallel (MPa)	Percent Difference (%)
Present Study	304L	552	445	22

DED Tensile Properties Compared to Conventional Materials?

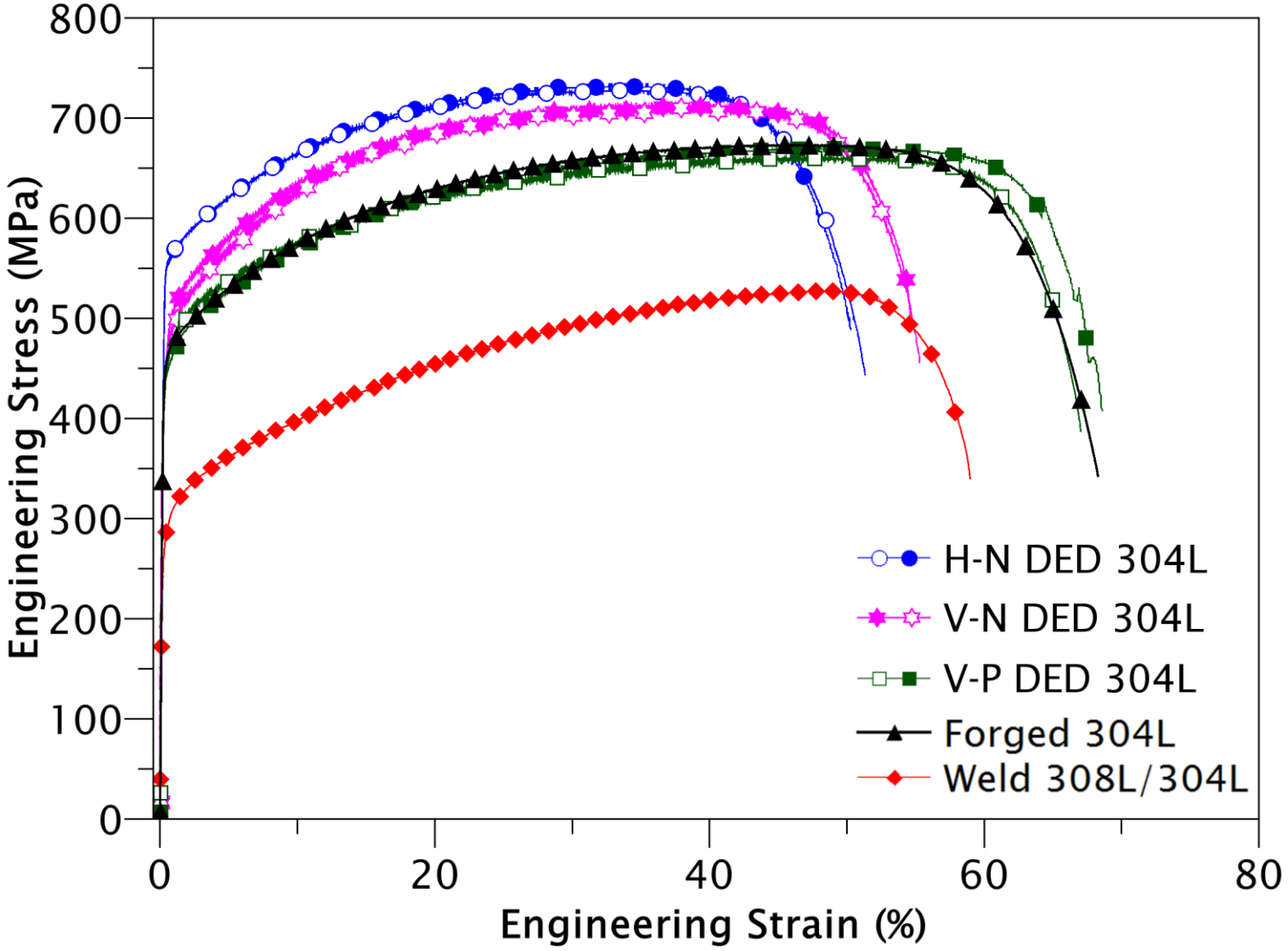


DED Tensile Properties Consistent with Conventional Materials



Ronevich JA, San Marchi CW, Balch DK. Pressure Vessels and Piping Conference (PVP 2017): ASME; 2017.
Jackson H, San Marchi C, Balch D, Somerday B, Michael J. Metall and Mat Trans A. 2016;47:4334-50.

DED Tensile Properties Consistent with Conventional Materials



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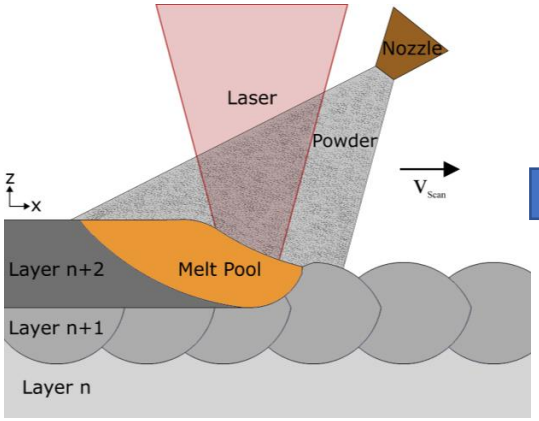
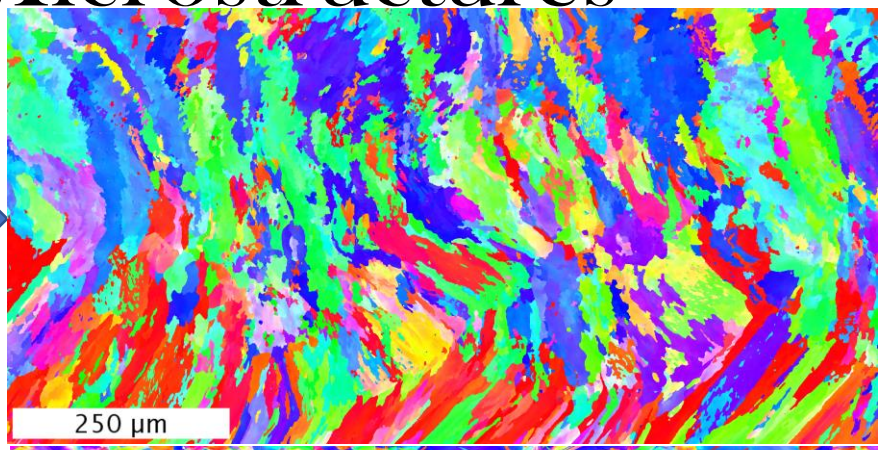
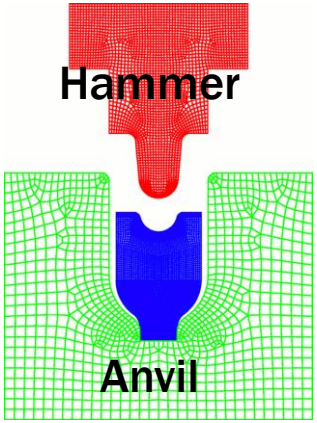
Jackson H, San Marchi C, Balch D, Somerday B, Michael J. Metall and Mat Trans A. 2016;47:4334-50.

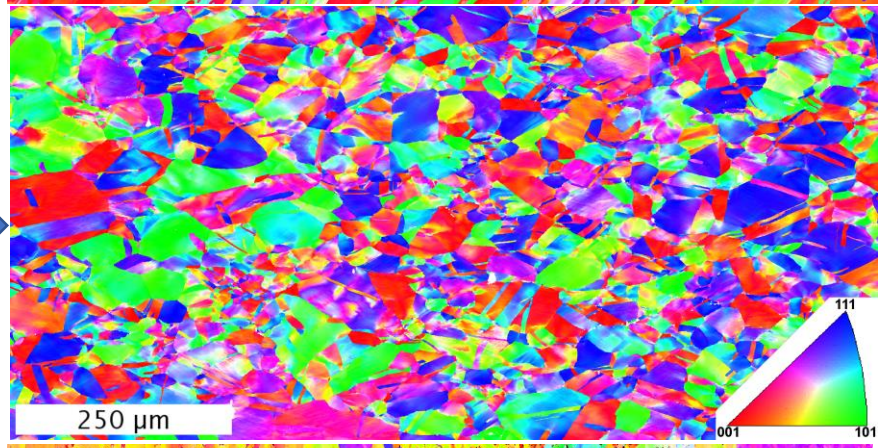
Processing → Distinct Microstructures

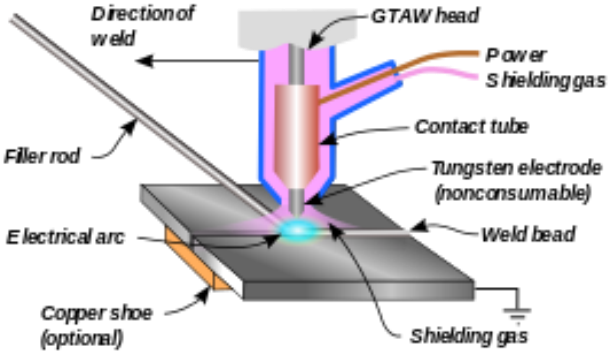






M.L. Chiesa, R.E. Jones, K.J. Perano, T.G. Kolda. Numiform 2004, American Institute of Physics, 2004, pp. 2080-2084.





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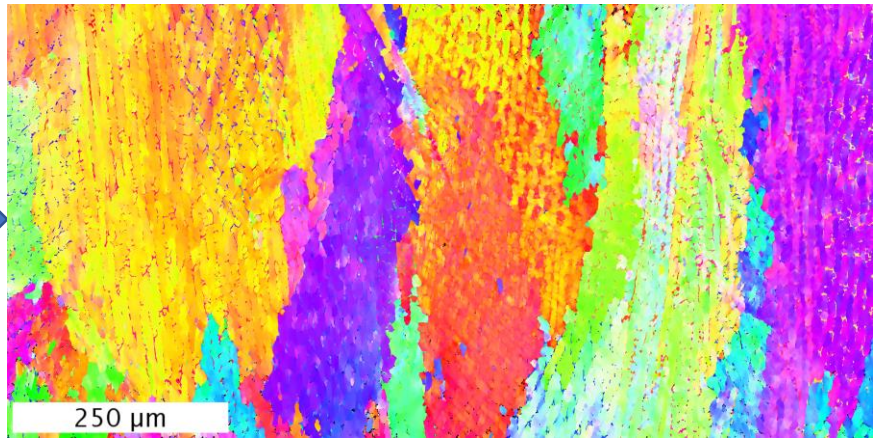
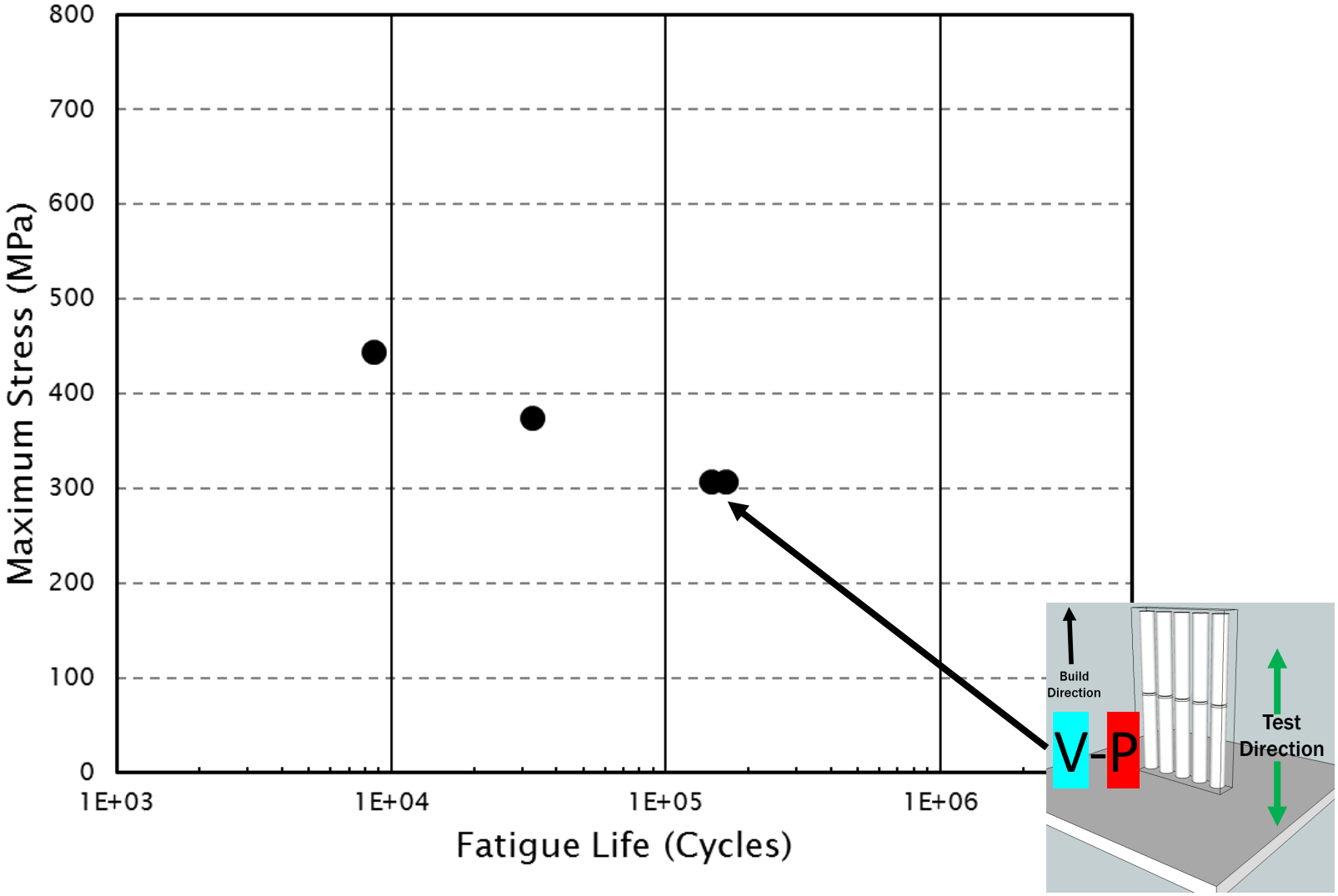


DED Fatigue Life



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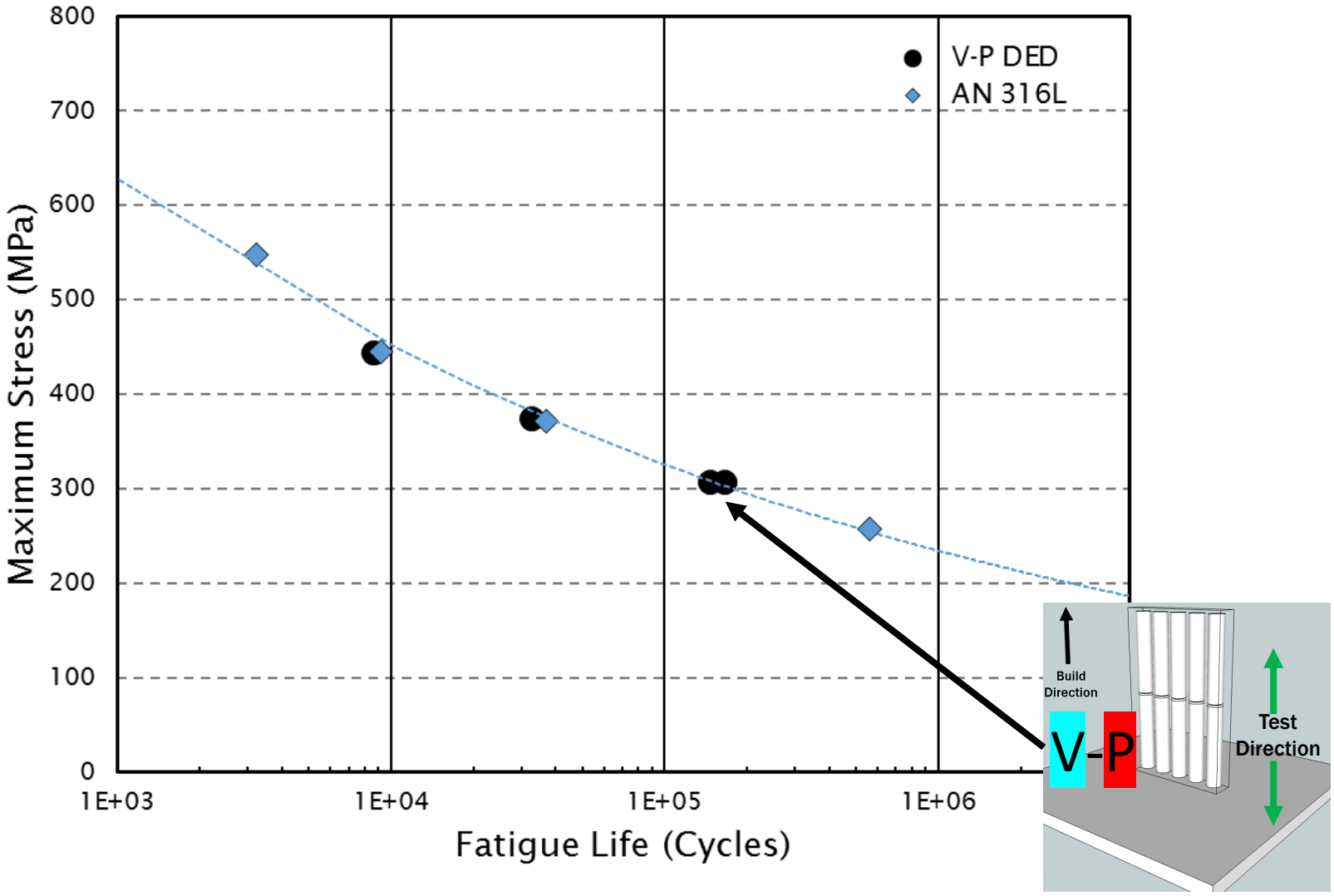
Nibur KA, San Marchi CW. Pressure Vessels and Piping Conference (2017): ASME; 2017.

DED Fatigue Life Consistent with Conventional Materials



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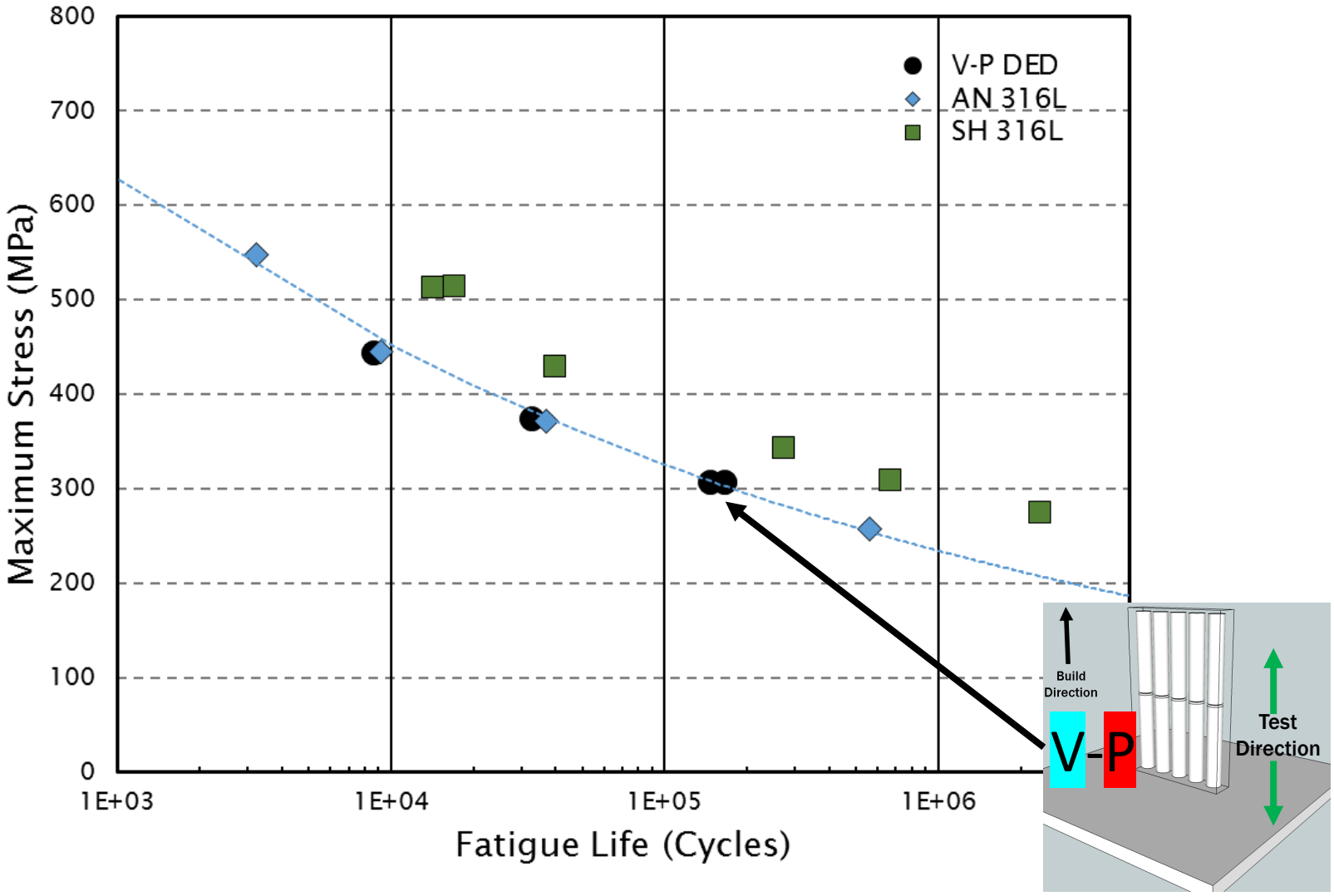

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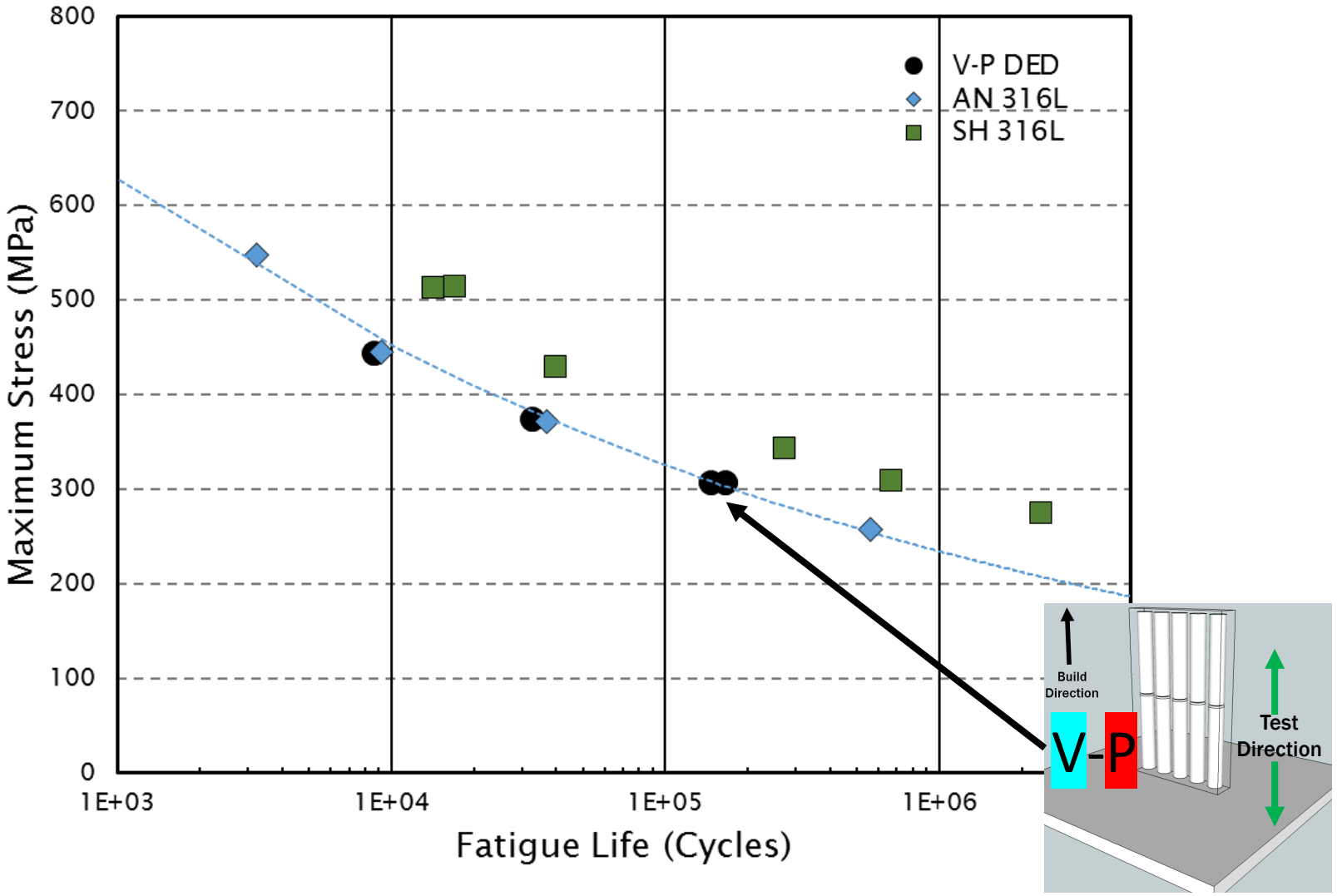
DED Fatigue Life Consistent with Conventional Materials

Yield Strength

Annealed = 280 MPa

Strain Hardened = 589 MPa



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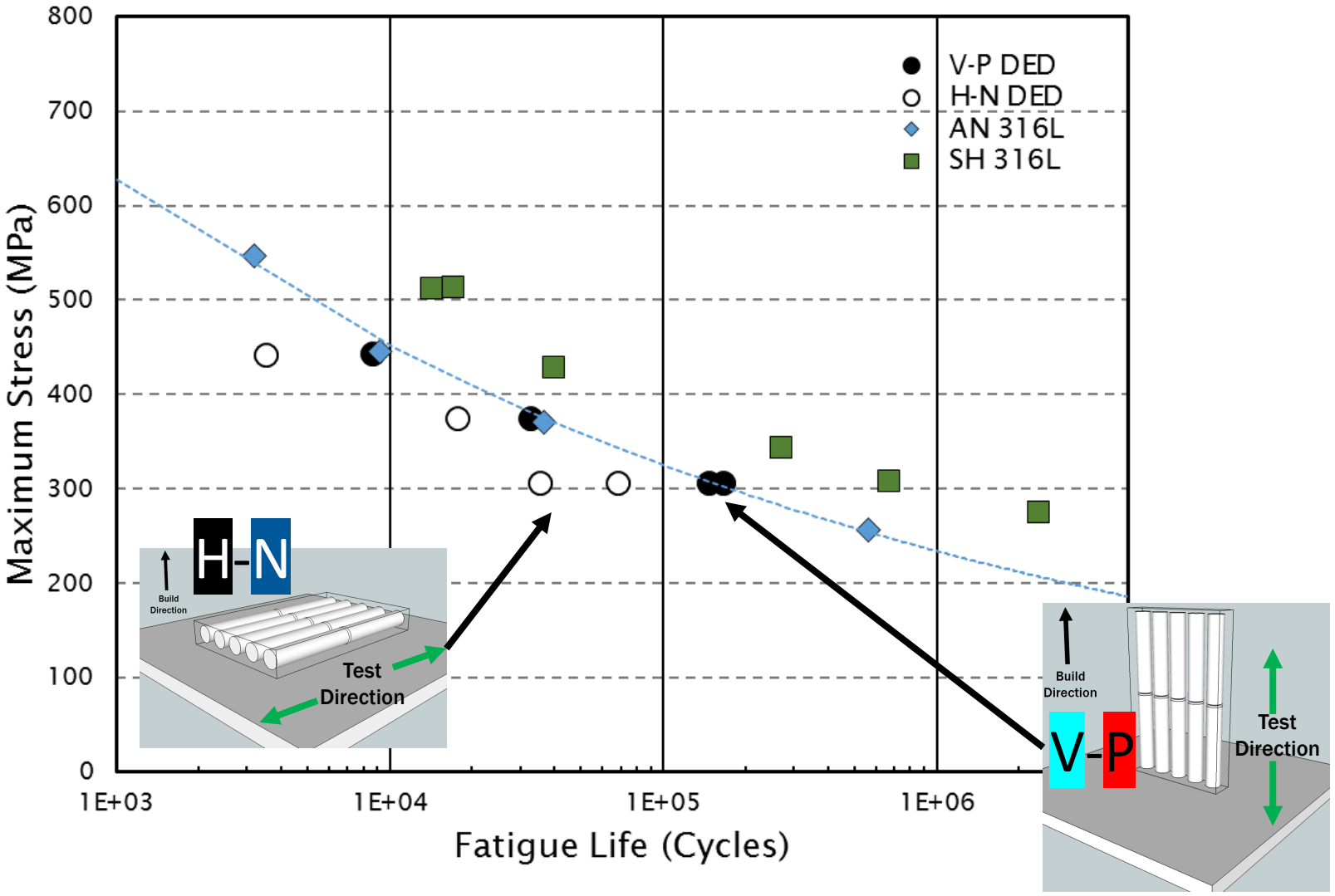
Build Orientation has Effect on DED Fatigue Behavior



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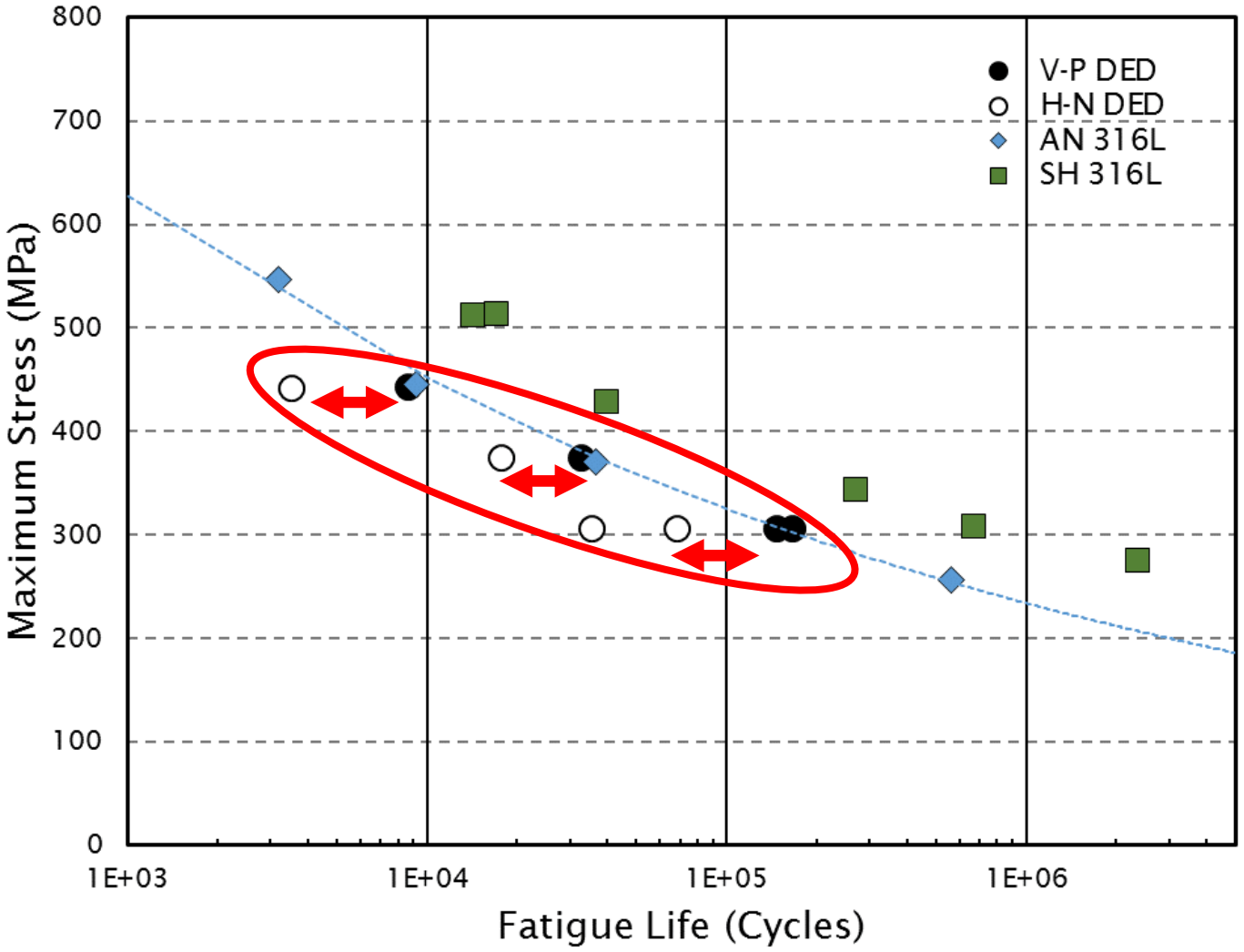

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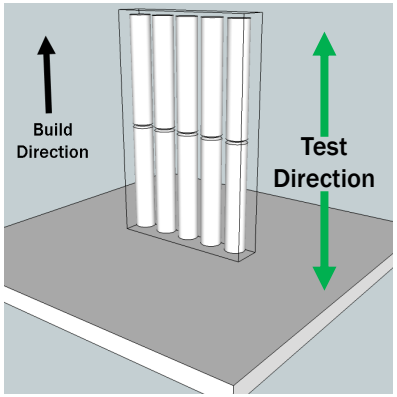
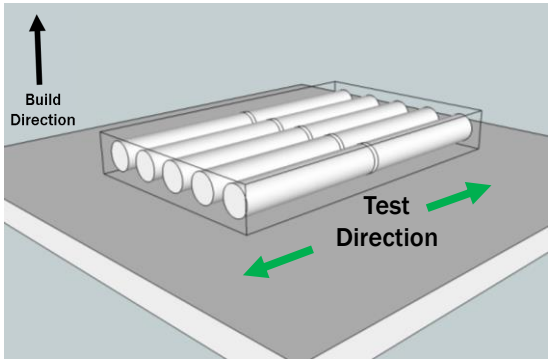
Fracture Surface Characterization Indicates Influence of Build Defects

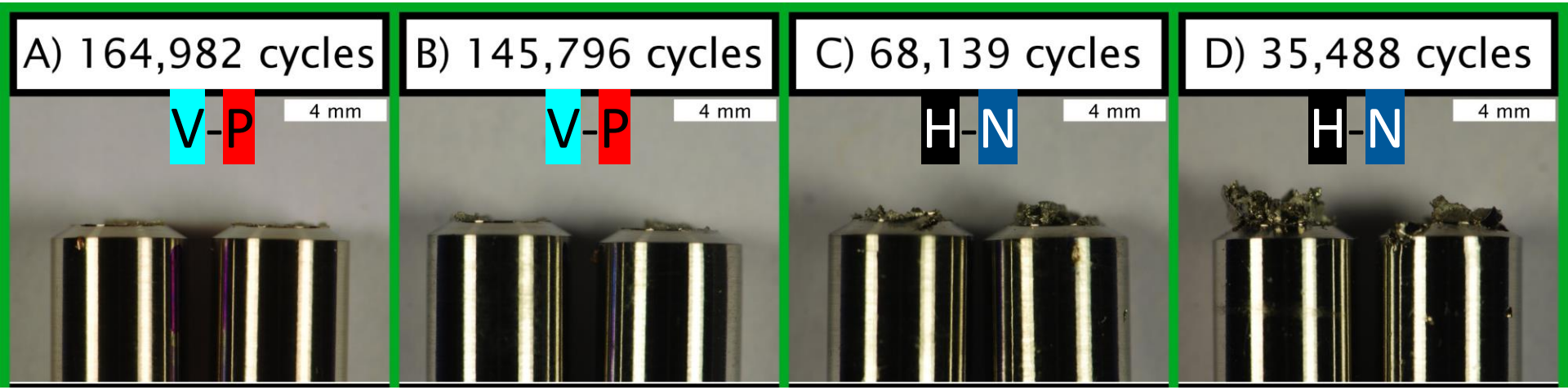
A) 164,982 cycles	B) 145,796 cycles	C) 68,139 cycles	D) 35,488 cycles
V-P	V-P	H-N	H-N



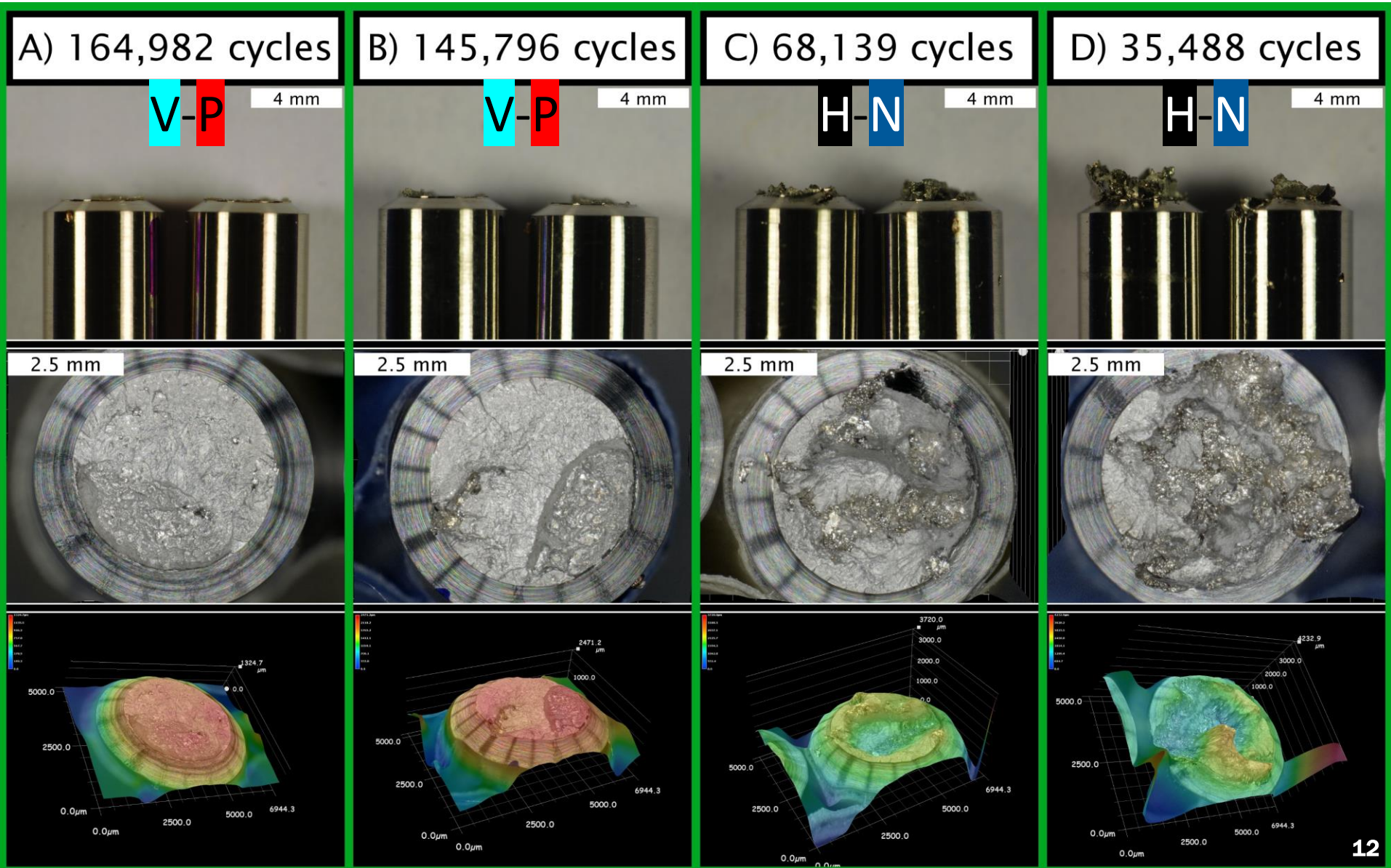


Max Stress = 305 MPa

Fracture Surface Characterization Indicates Influence of Build Defects



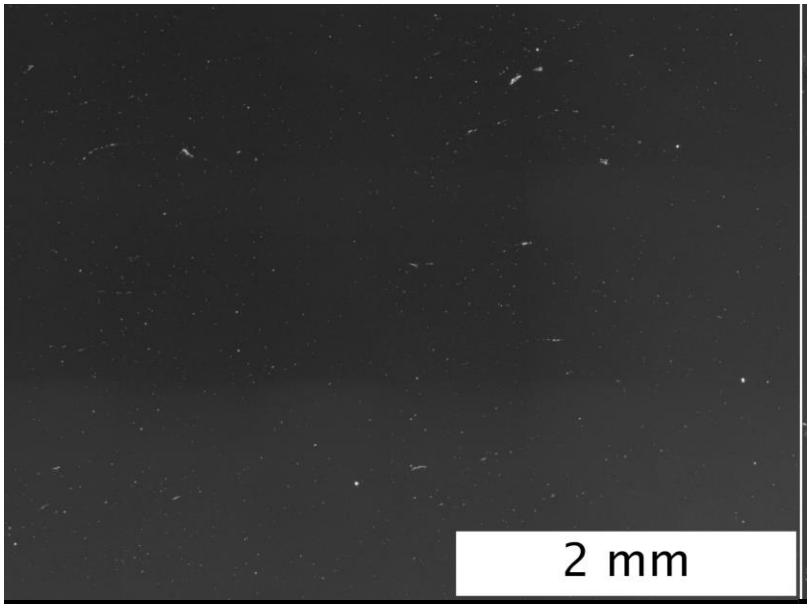
Fracture Surface Characterization Indicates Influence of Build Defects



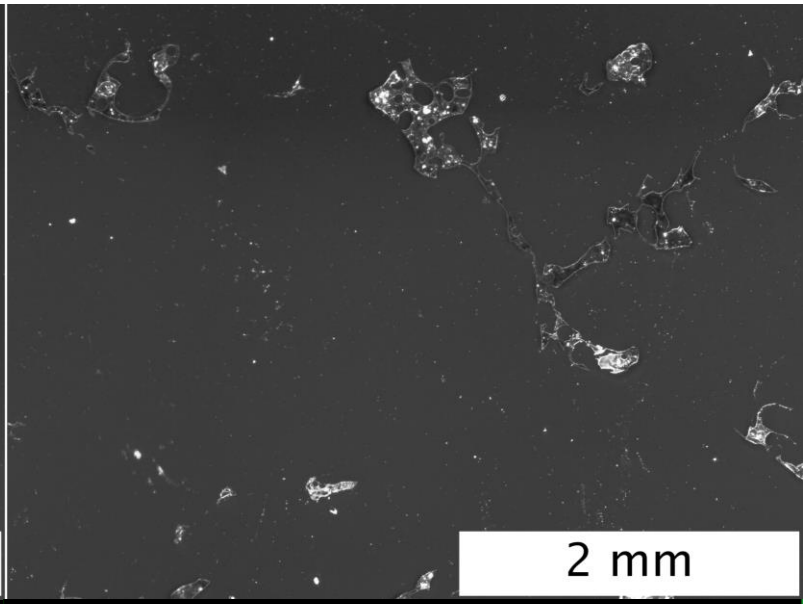
Lack of Fusion (LoF) Defects

>99% Dense **~97% Dense**

V-P

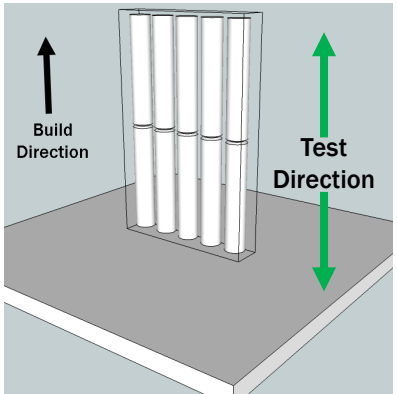


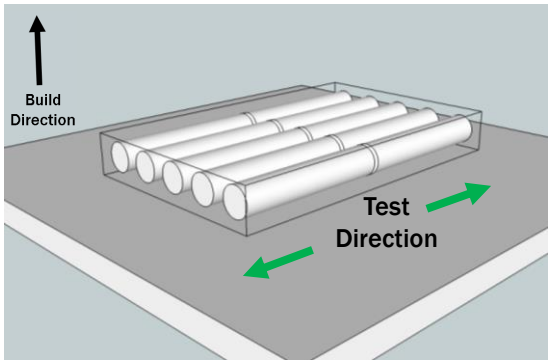
A) 164,982 cycles



C) 68,139 cycles

H-N





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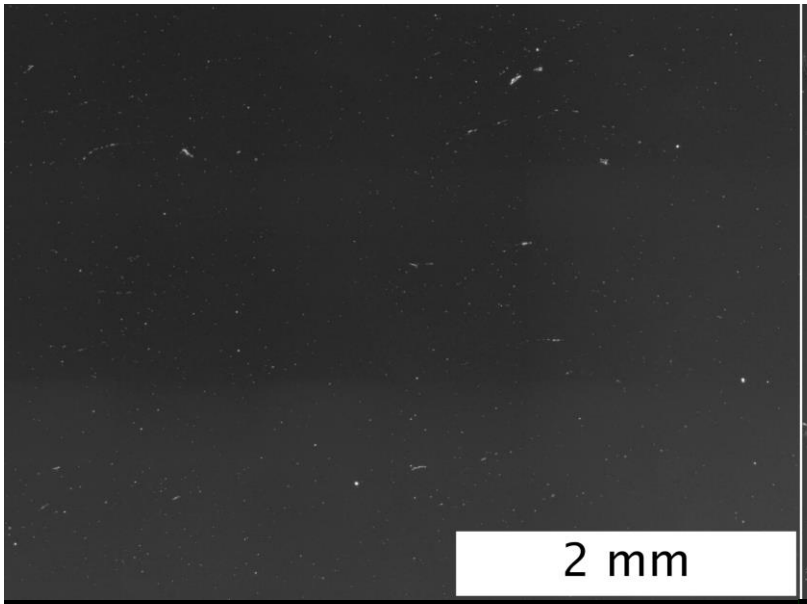
V-P



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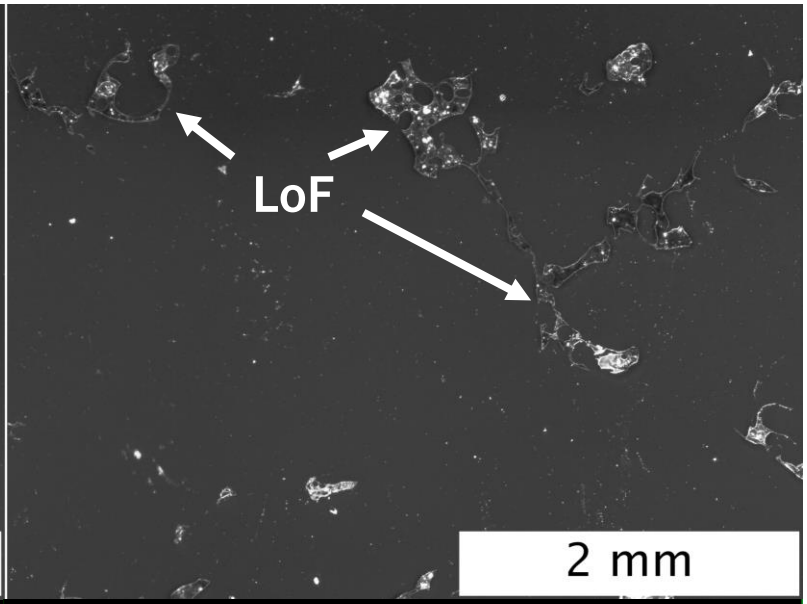
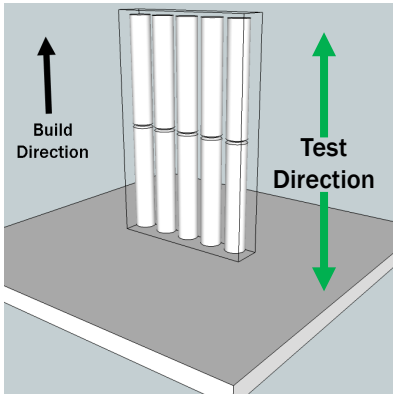
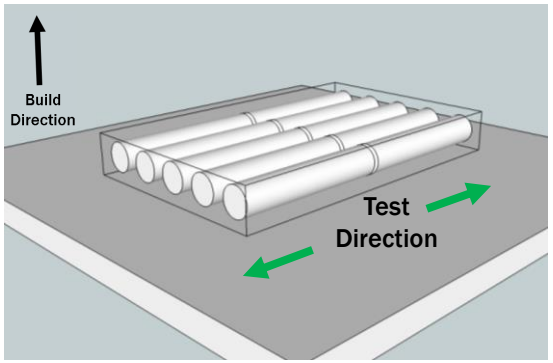


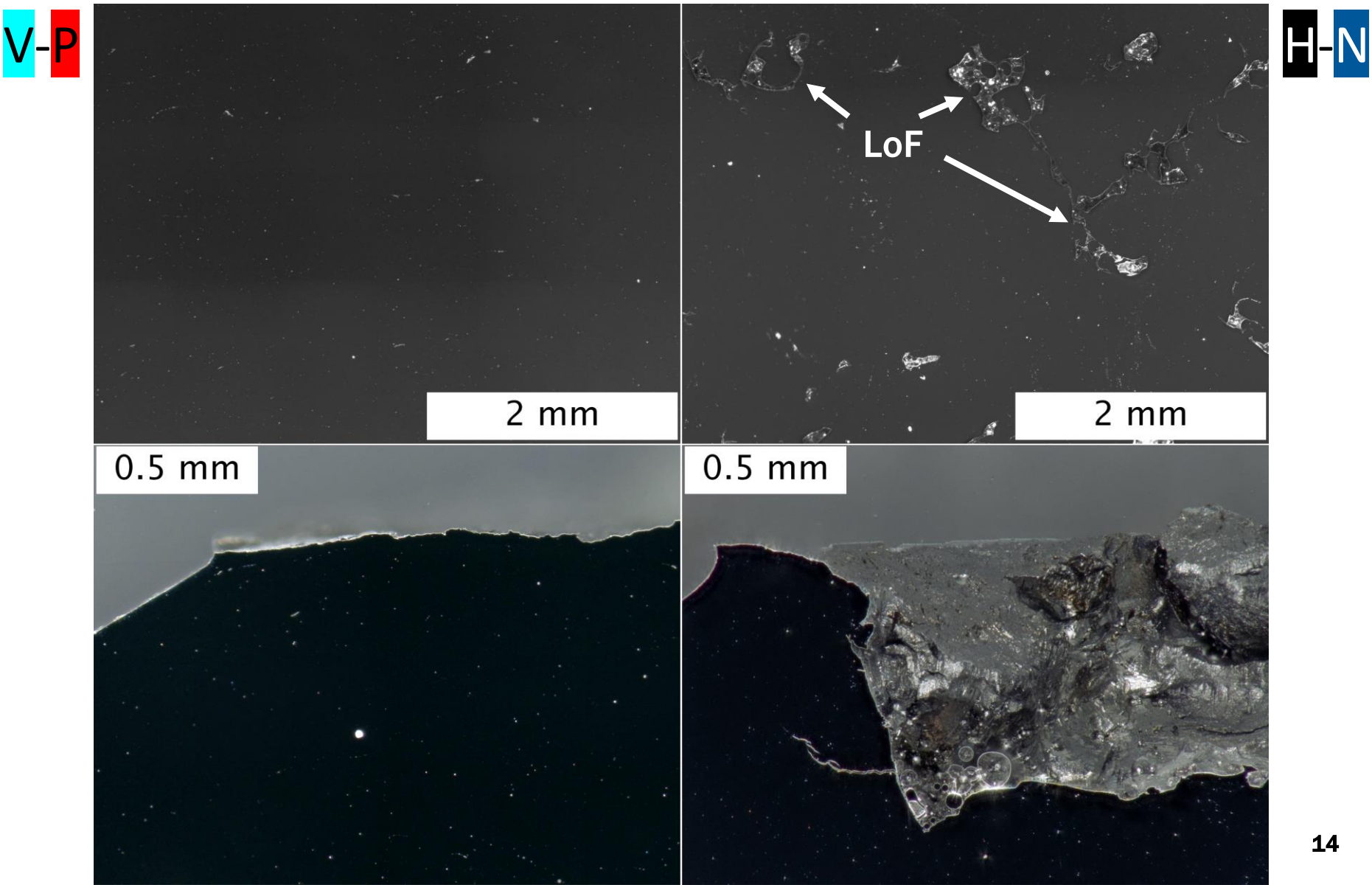
C) 68,139 cycles

H-N

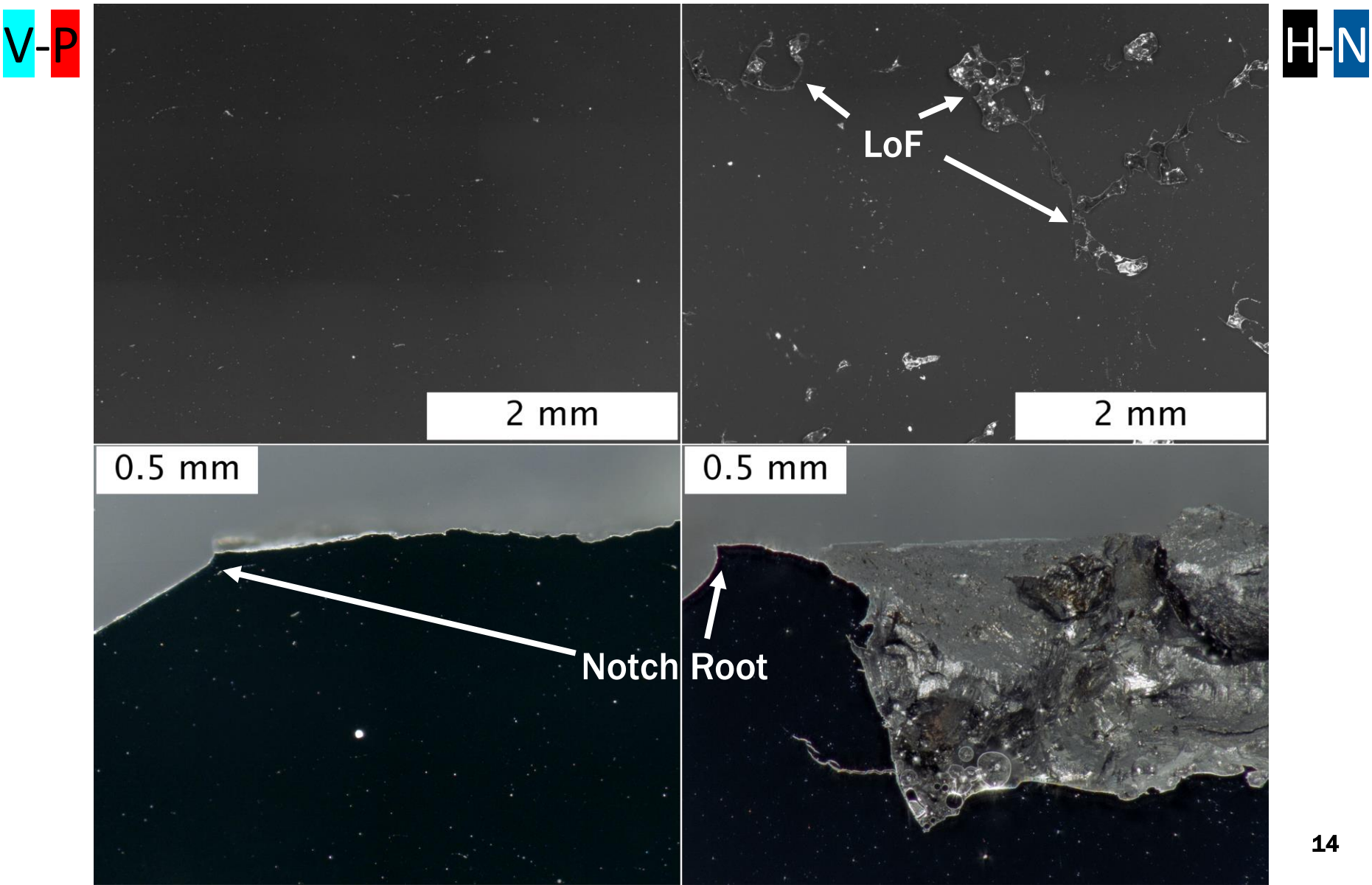




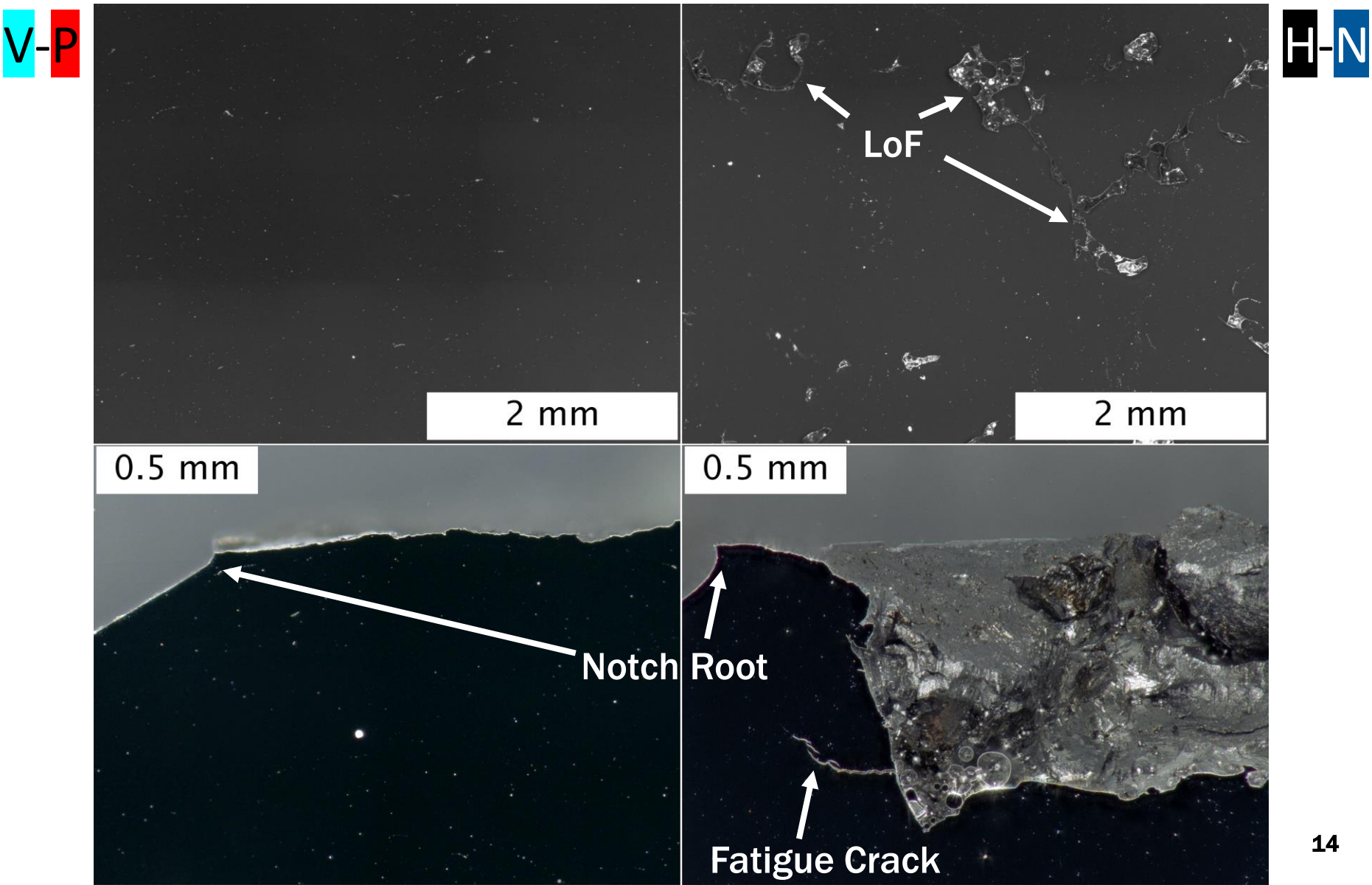
Fatigue Crack Propagation at LoF Defects



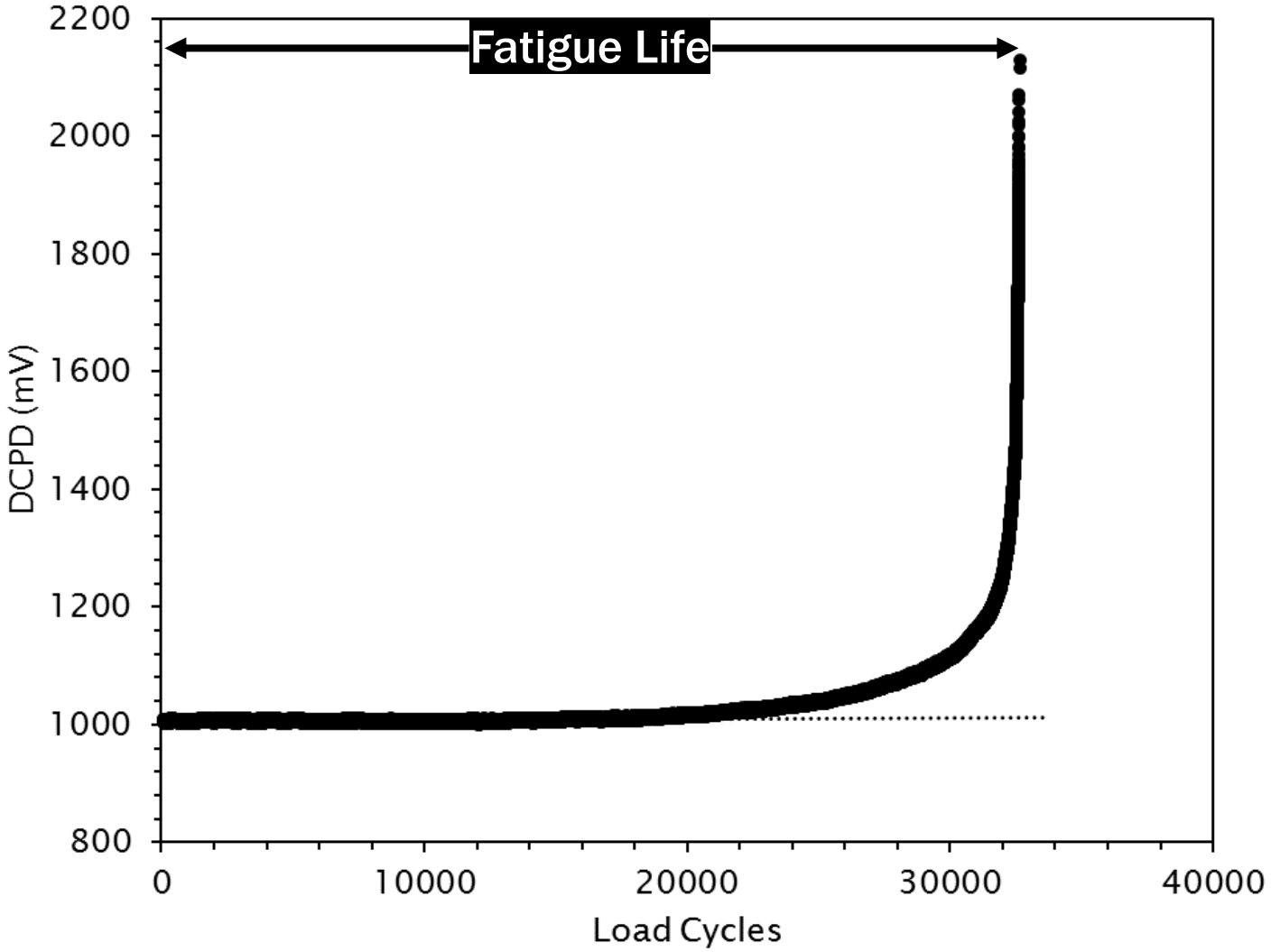
Fatigue Crack Propagation at LoF Defects



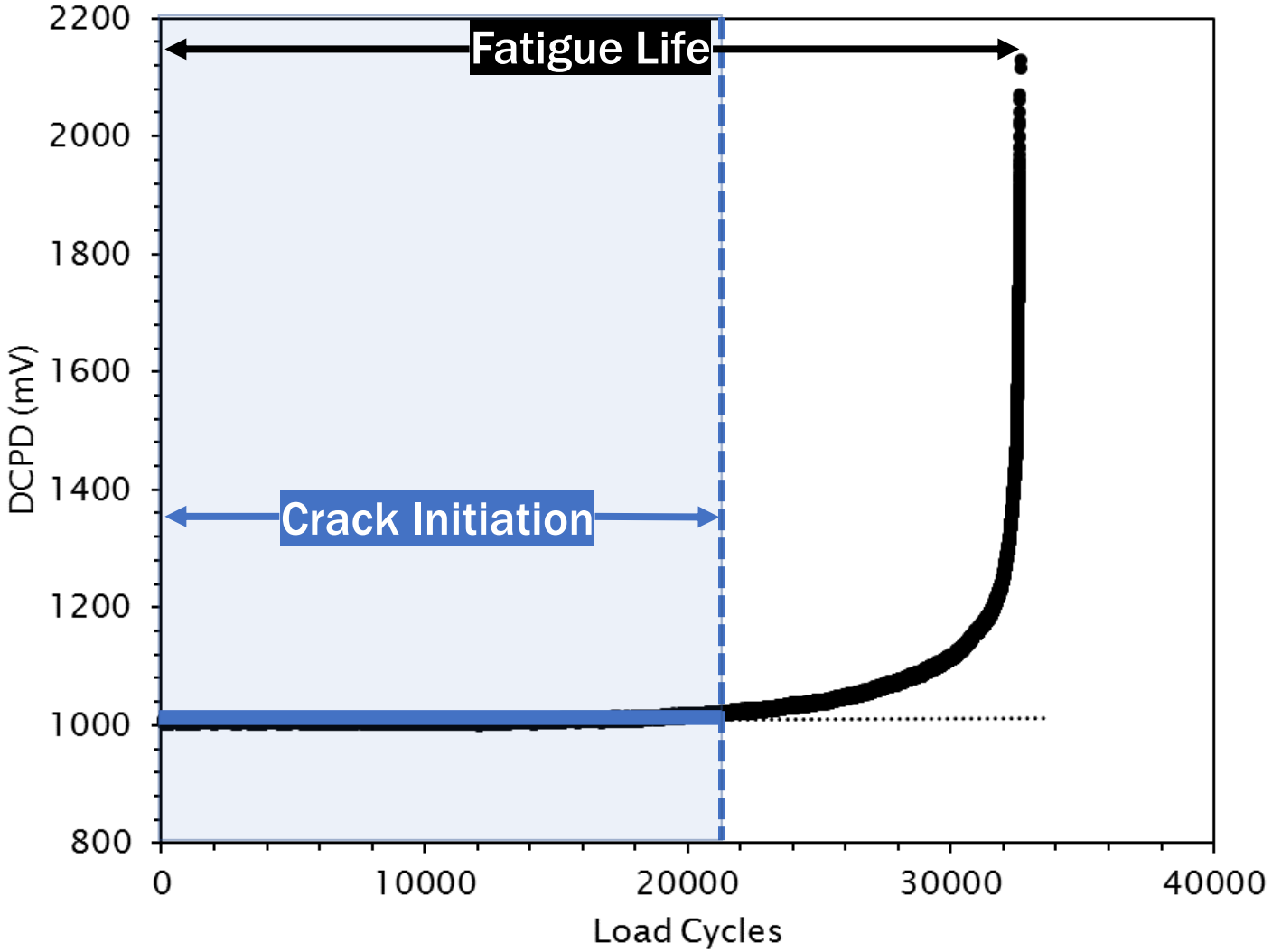
Fatigue Crack Propagation at LoF Defects



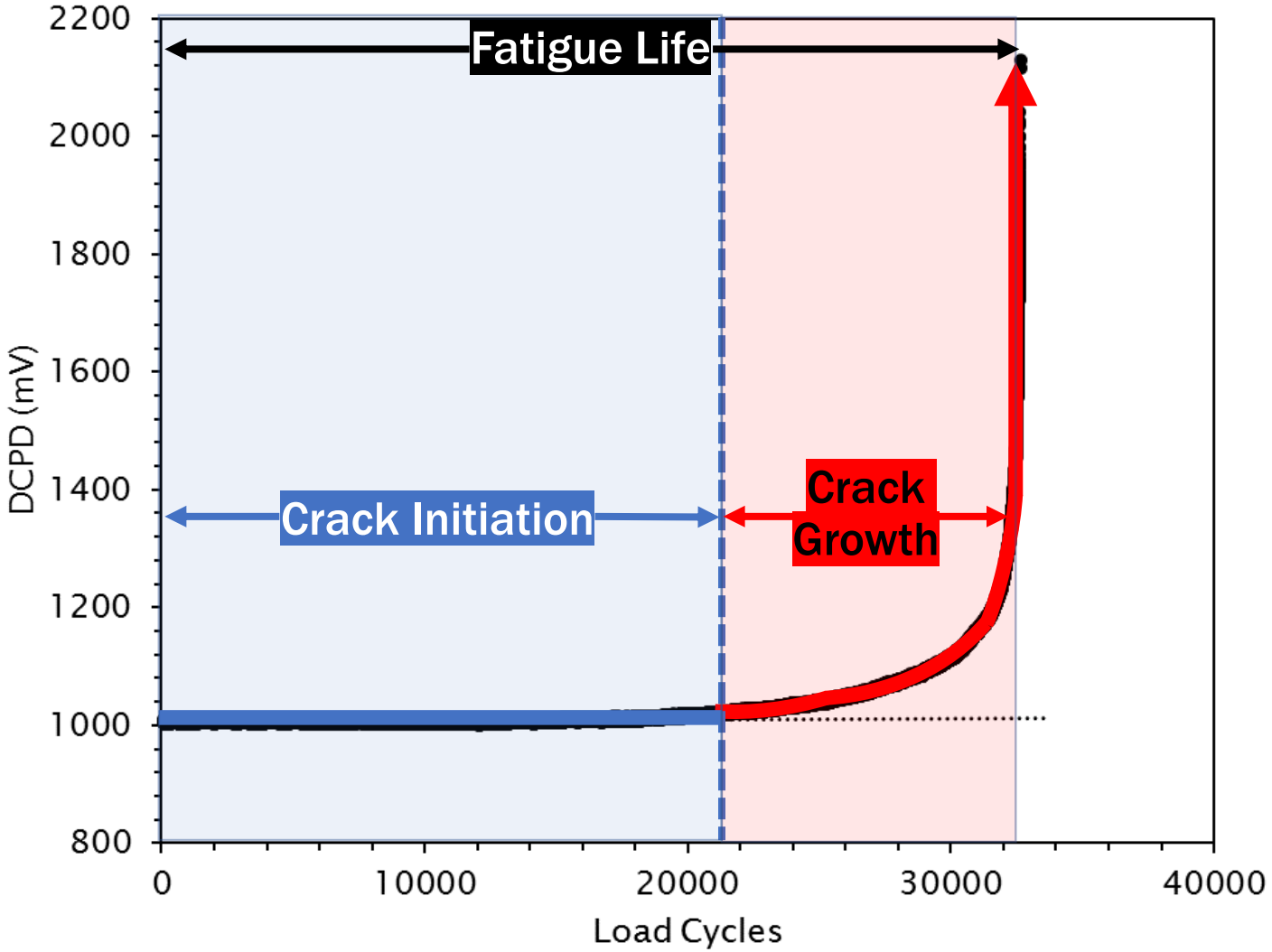
Direct Current Potential Difference (DCPD)



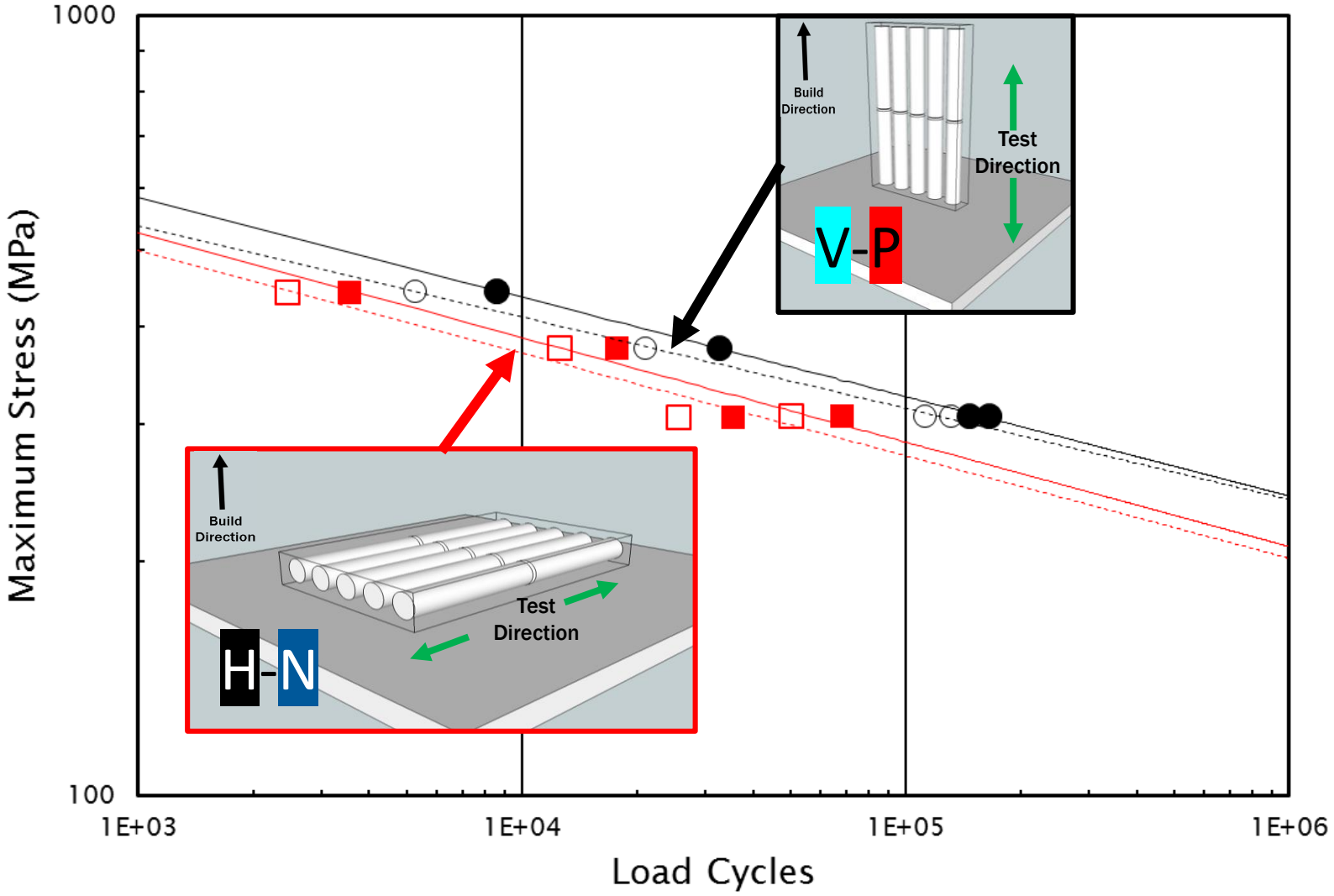
DCPD for Fatigue Crack Initiation



DCPD for Fatigue Crack Initiation

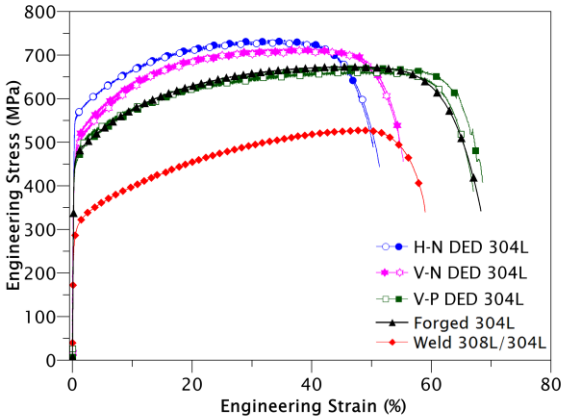


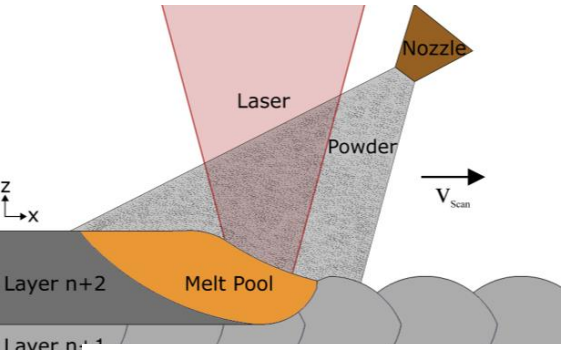
Fatigue Crack Initiation Promoted by LoF Defects in H-N DED

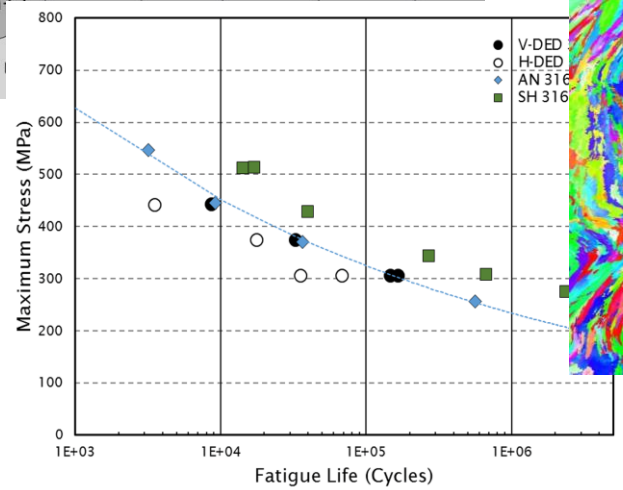


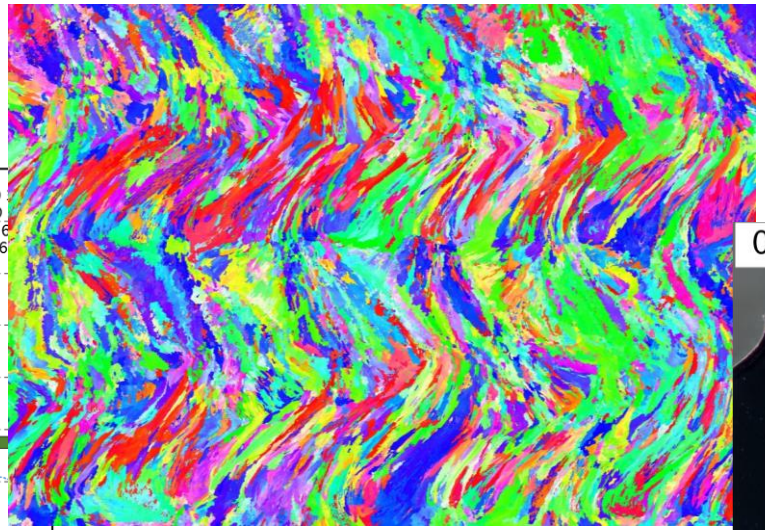
Summary

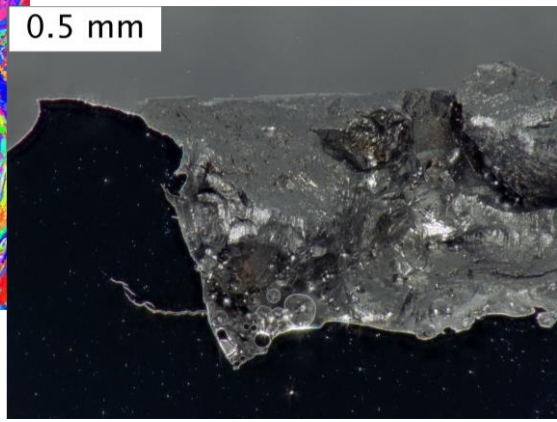
- **Specimen orientation has little effect on tensile properties**



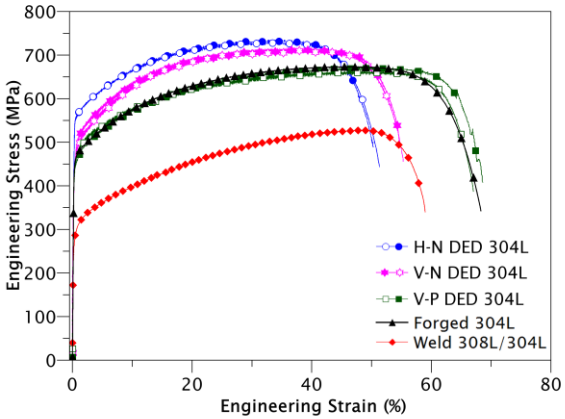




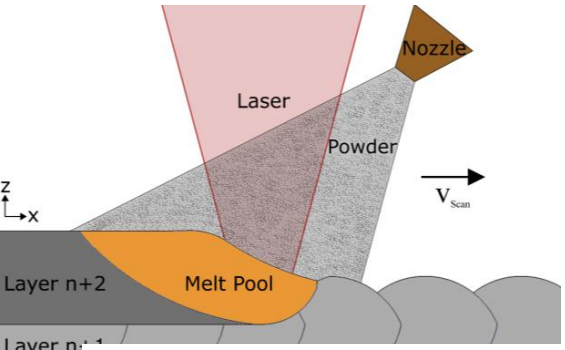


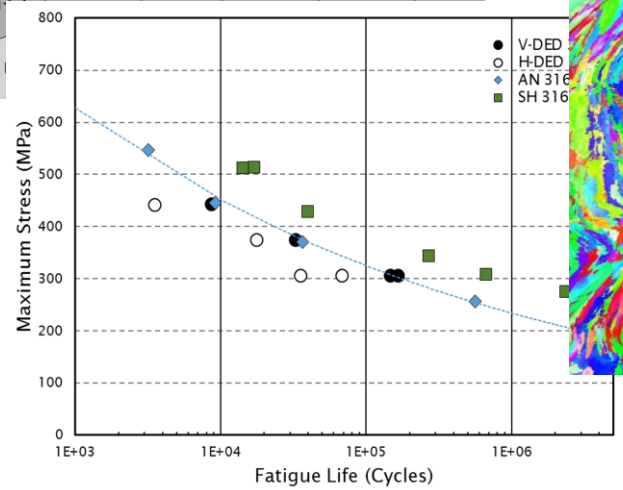


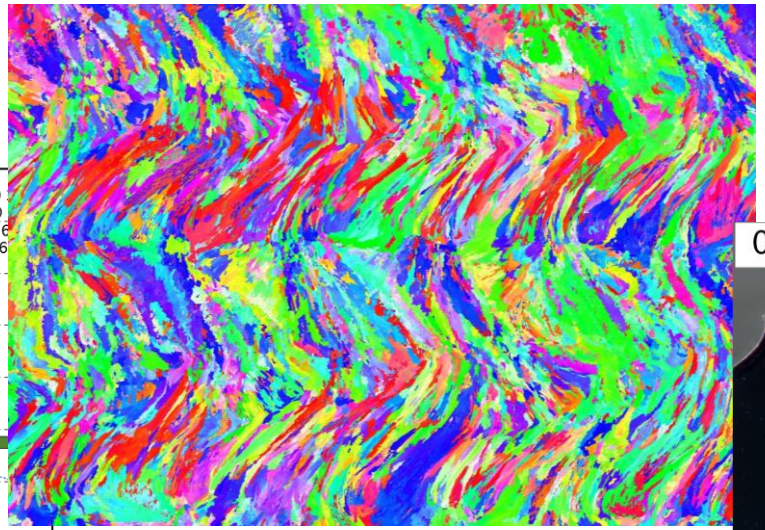
Summary

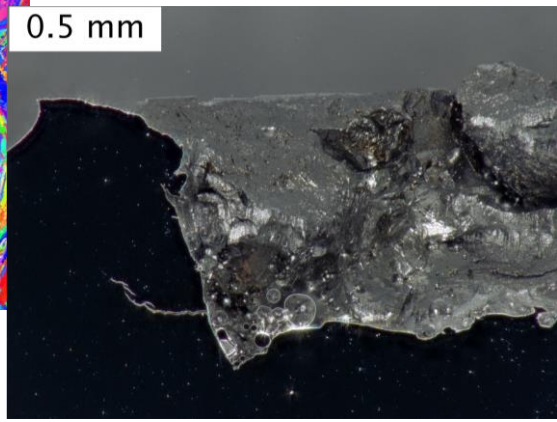


- Specimen orientation has little effect on tensile properties
- Build orientation has significant effect on tensile and fatigue properties

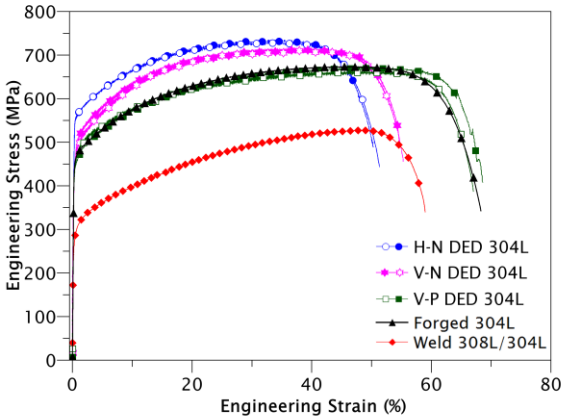




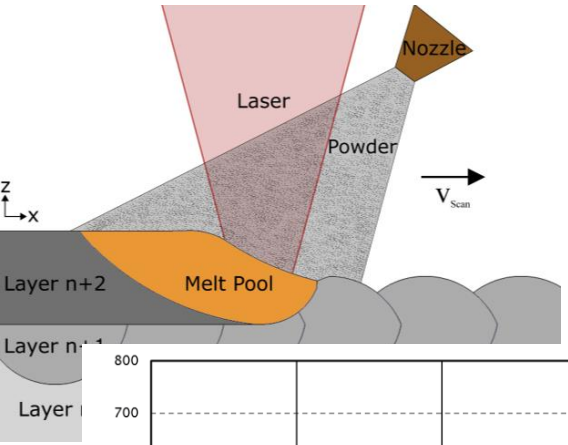


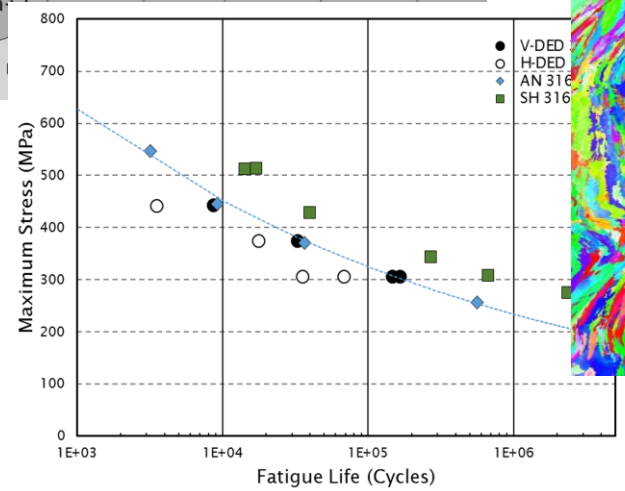


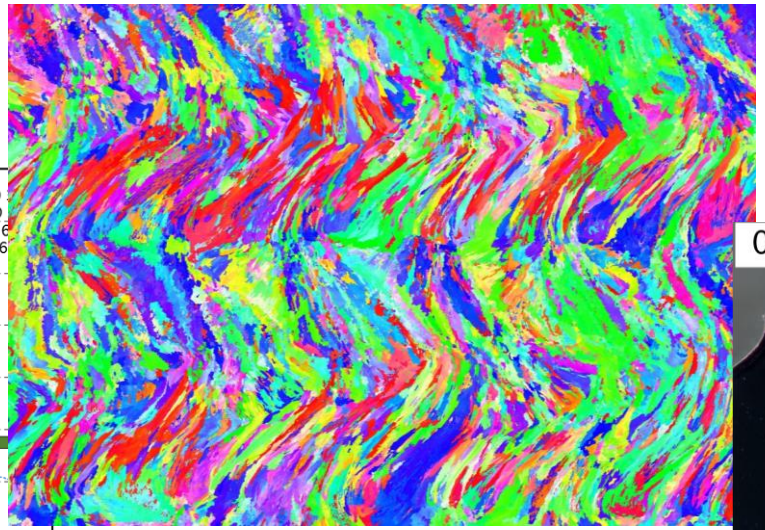
Summary

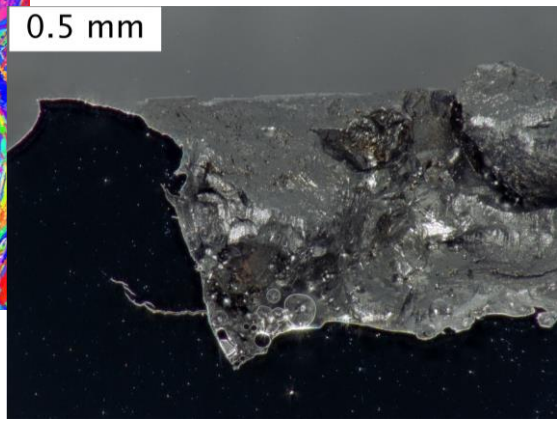


- Specimen orientation has little effect on tensile properties
- Build orientation has significant effect on tensile and fatigue properties
- Differences in microstructural and build defect populations cause of build orientation effects

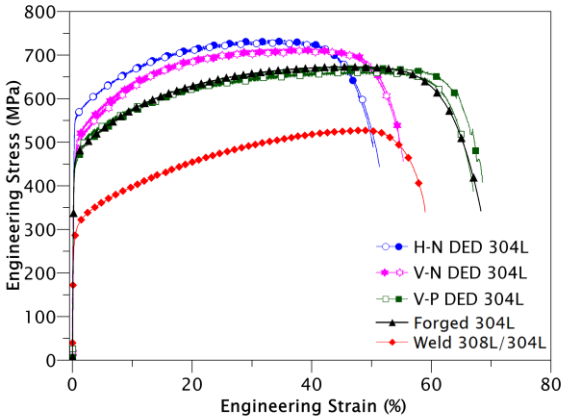




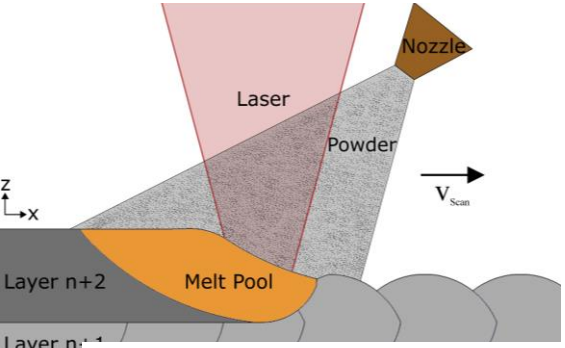


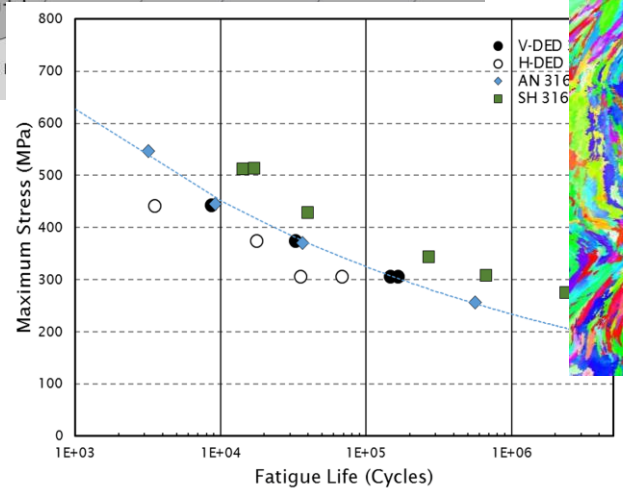


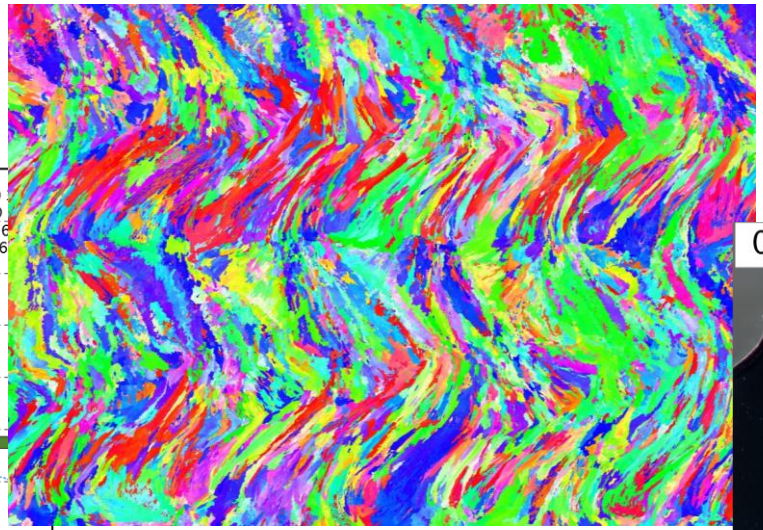
Conclusions

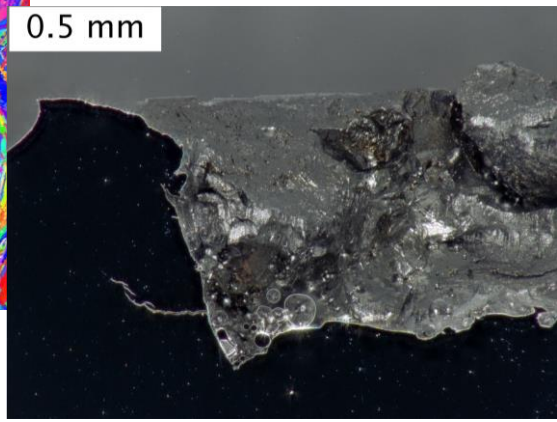


As-deposited DED material exhibit comparable properties with conventional materials

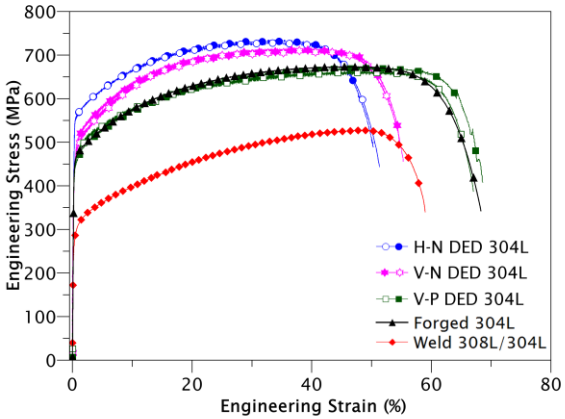






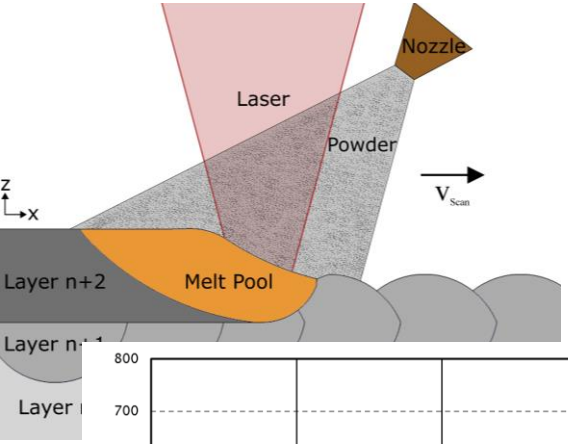


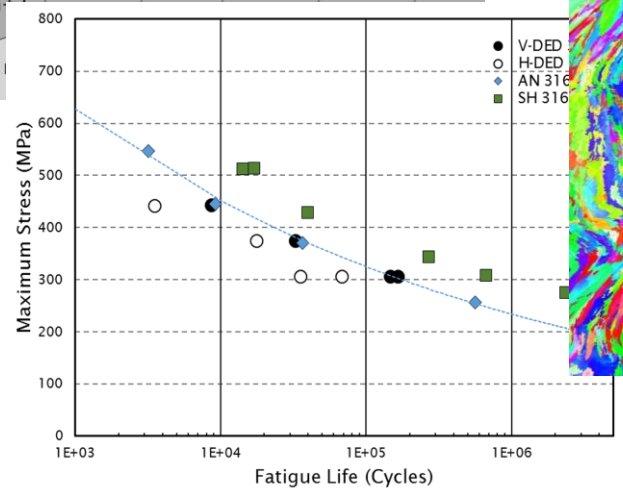
Conclusions

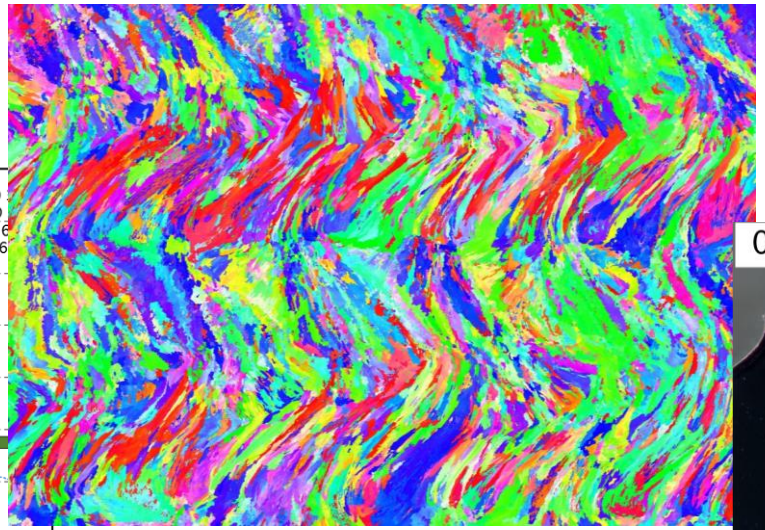


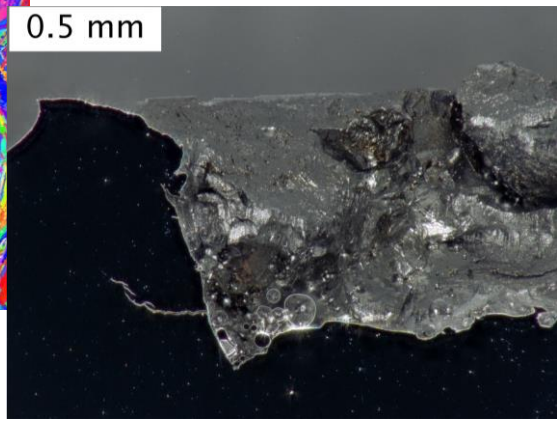
As-deposited DED material exhibit comparable properties with conventional materials

Build geometry influences defect development in as-deposited DED

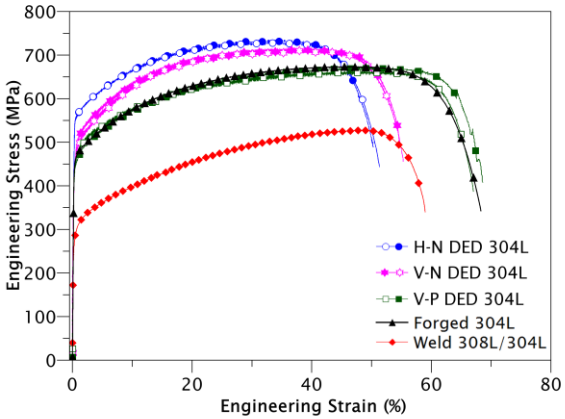








Conclusions



As-deposited DED material exhibit comparable properties with conventional materials

Build geometry influences defect development in as-deposited DED

AM designs must account for defect development