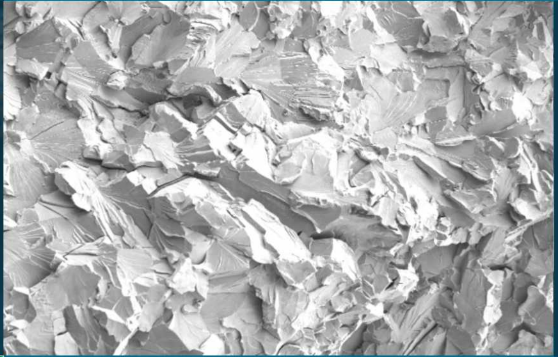
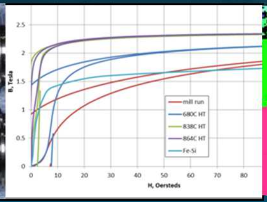
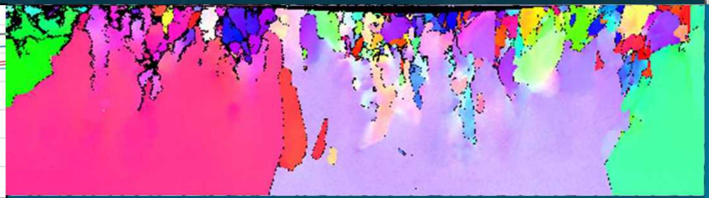
SAND2019-11409C

Location-Specific Mechanical Property Enhancement of Atomically Ordered Fe-Co-V Soft Magnetic Alloys







PRESENTED BY

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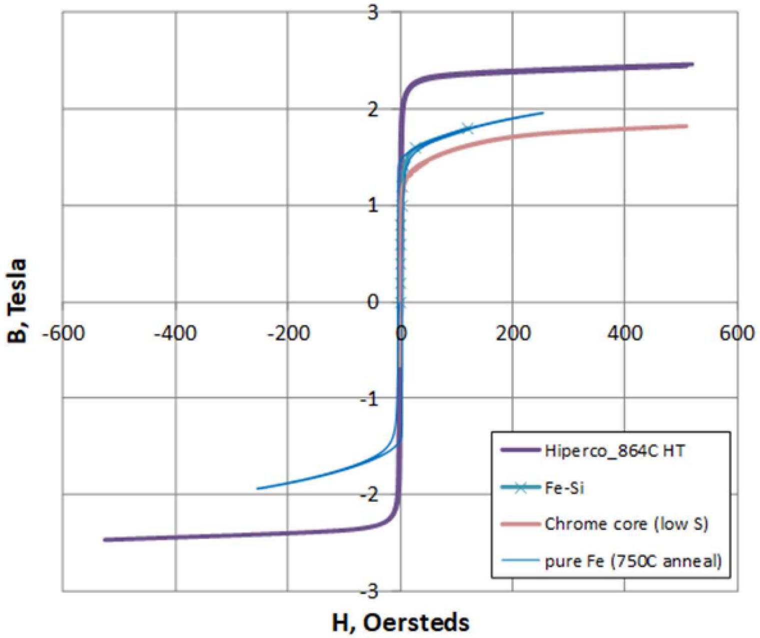
Why Use FeCoV Alloys?

- FeCoV alloys are <u>ordered</u> soft magnetic materials used for FeCoV alloys offer the highest magnetic saturation of any known alloy system
- Fe-49Co-2V (also known as Hiperco® 50A or 2V Permendur) is an ideal material for high-efficiency solenoids, motors, transformer cores, etc. where volume is limited
- While magnetic properties are ideal, mechanical properties are generally regarded as poor and are often design-limiting

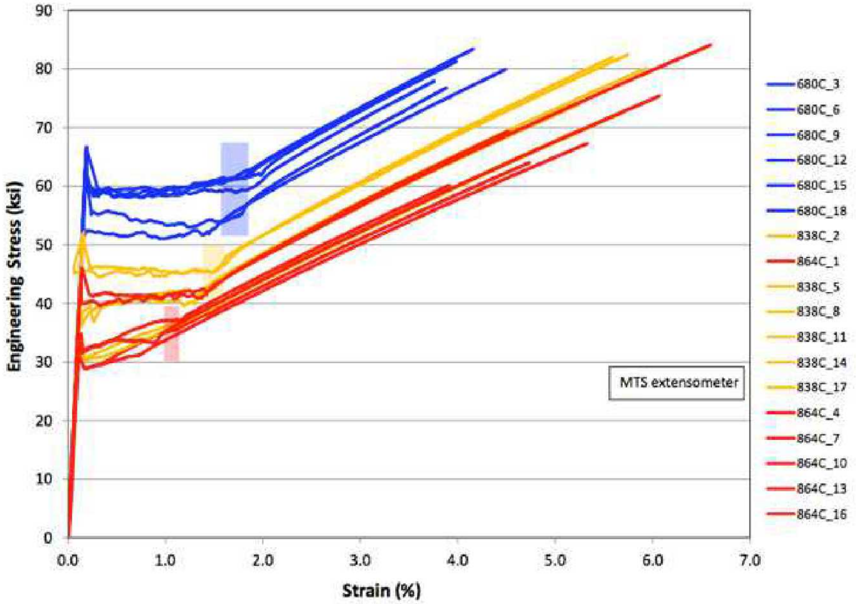
<u>Flight Surface Actuators</u>

Image Source: https://www.rockwellcollins.com/

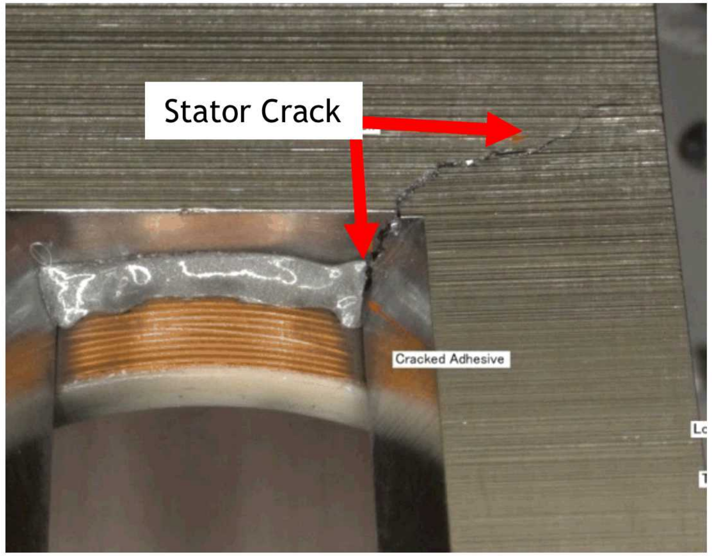
<u>FeCoV alloys offer superior B-H characteristics</u>



<u>Low ductility is characteristic of FeCo2V (Hiperco 50A)</u>



<u>Low ductility can lead to brittle failure in demanding environments</u>



Brittle characteristics of FeCoV alloys are the result of long-range atomic order

- Unusual mechanical behavior of FeCo2V is the result the atomic order of the B2 phase
- Material processing to circumvent ordering comes at the expense of 'soft' magnetic properties

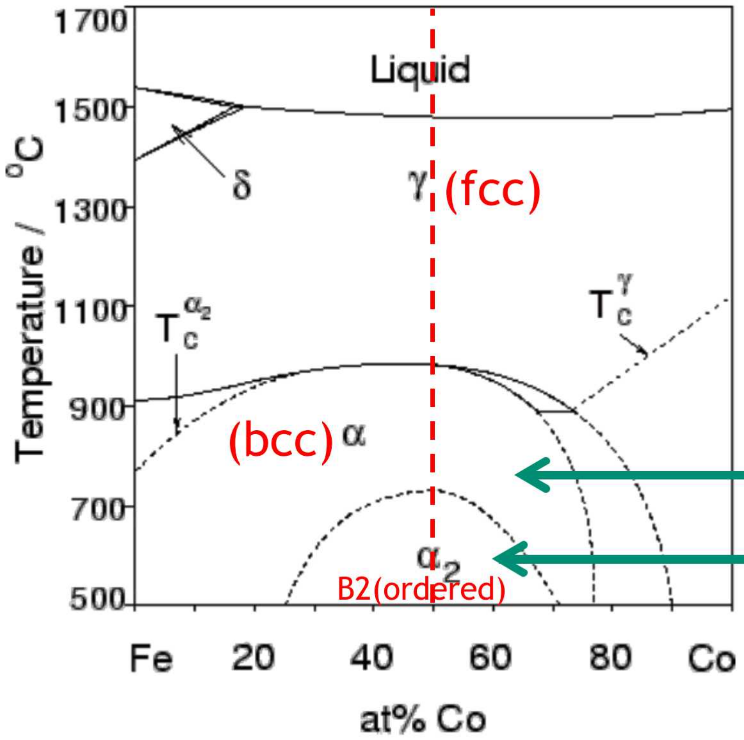
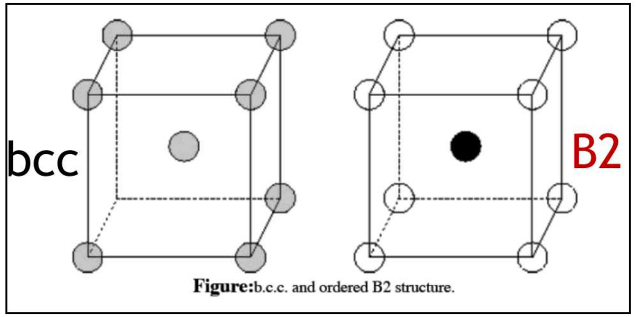


Figure: The Fe-Co binary diagram as given in [5]. T_c denotes the Curie temperature.

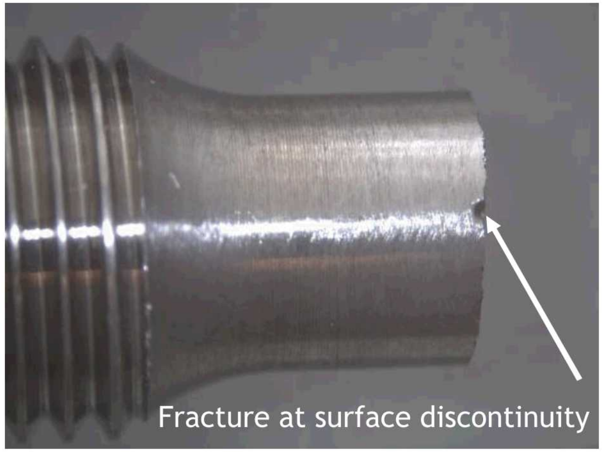


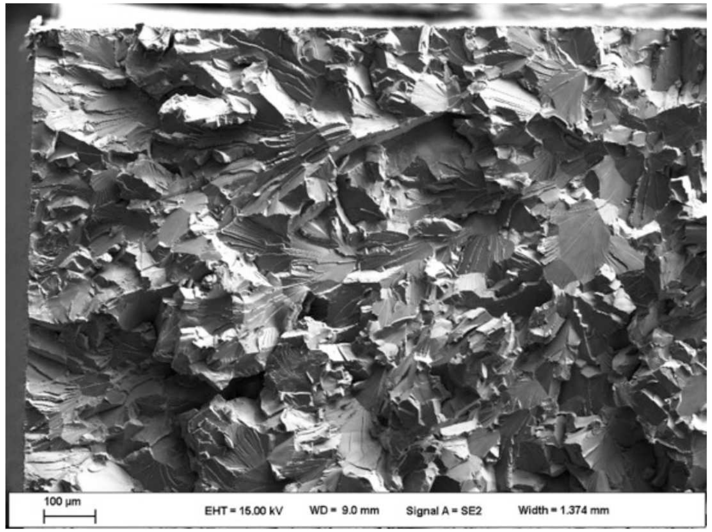
Crystal structures of FeCo2V alloy

bcc: Good mechanical properties, OK magnetic properties

B2: Ordered structure has poor mechanical properties, Excellent magnetic properties

FeCo alloys are surface-notch sensitive and exhibit surface-nucleated fracture





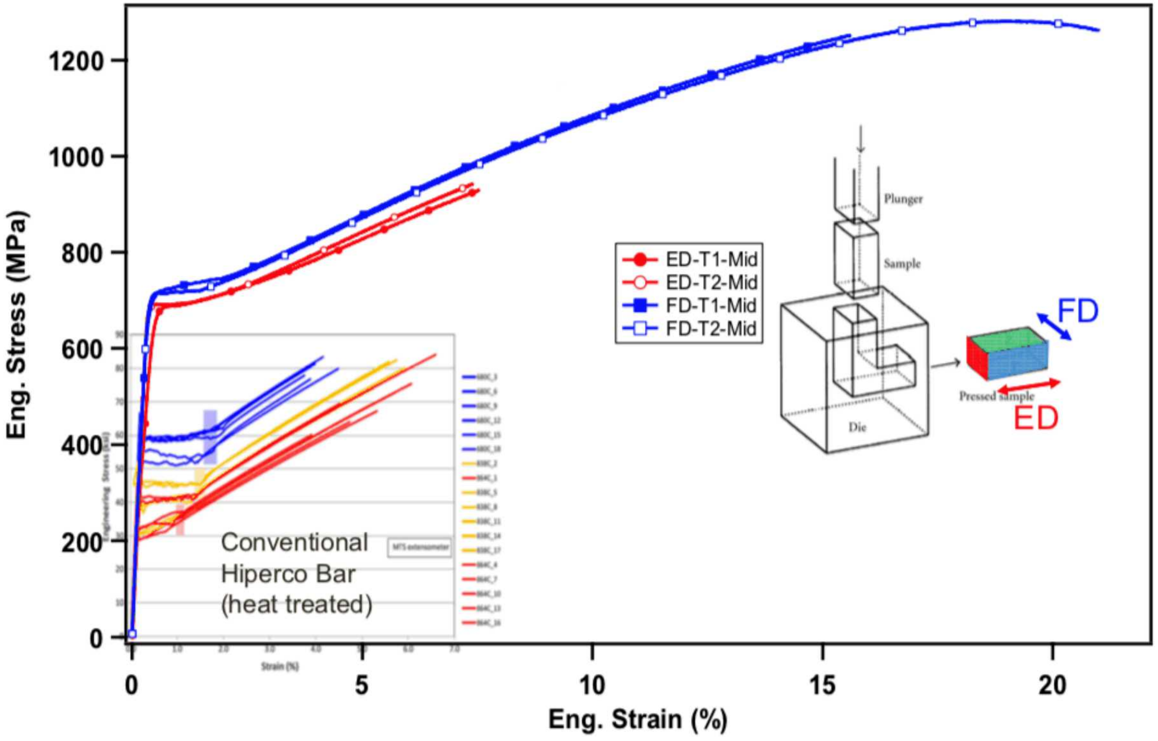
Mechanical failure results with no necking and accompanying microscopic brittle features (inter-/transgranular cleavage)

T. Sourmail, *Progress in Materials Science,* vol. 50, no. 7, pp. 816-880, 2005/09/01/ 2005.

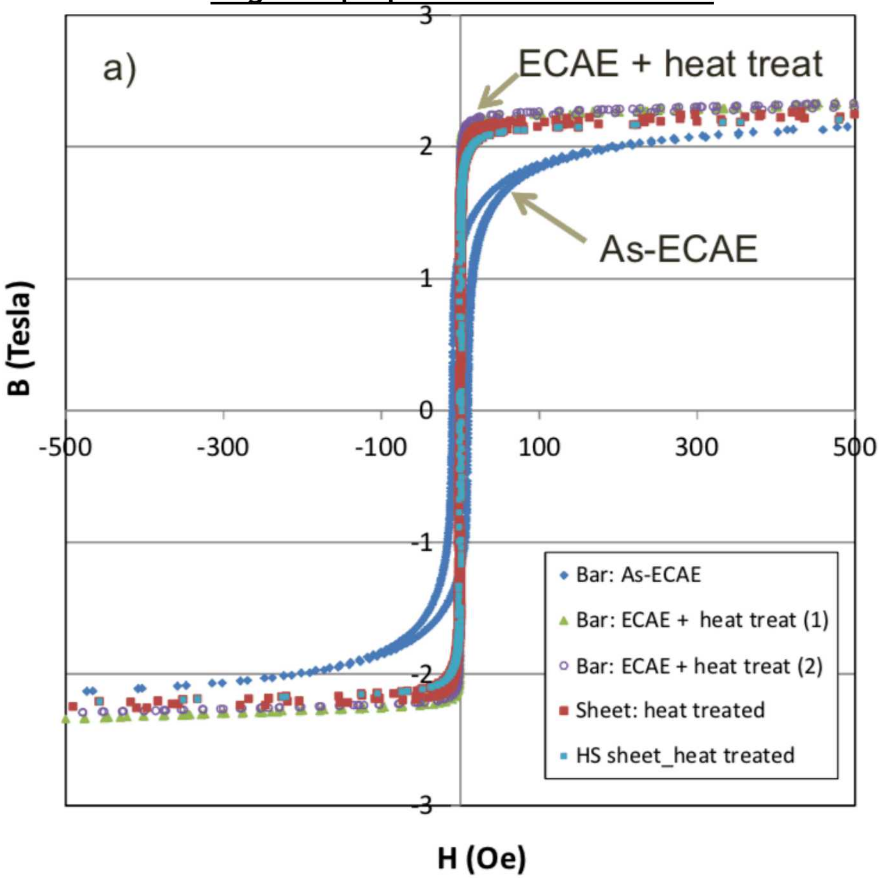
Bulk material processing techniques have been developed to overcome poor FeCo2V mechanical properties…at the expense of magnetic properties

- Several SNL studies have examined equal channel angular extrusion (ECAE) as a severe plastic deformation processing technique to create highly grain refined FeCo2V to improve strength
- Typical annealing treatments (830-860°C, 2 hours) to restore soft magnetic behavior eliminates ECAE refinement

ECAE can result in significant improvement to FeCo2V tensile properties



Magnetic properties of ECAE FeCo2V

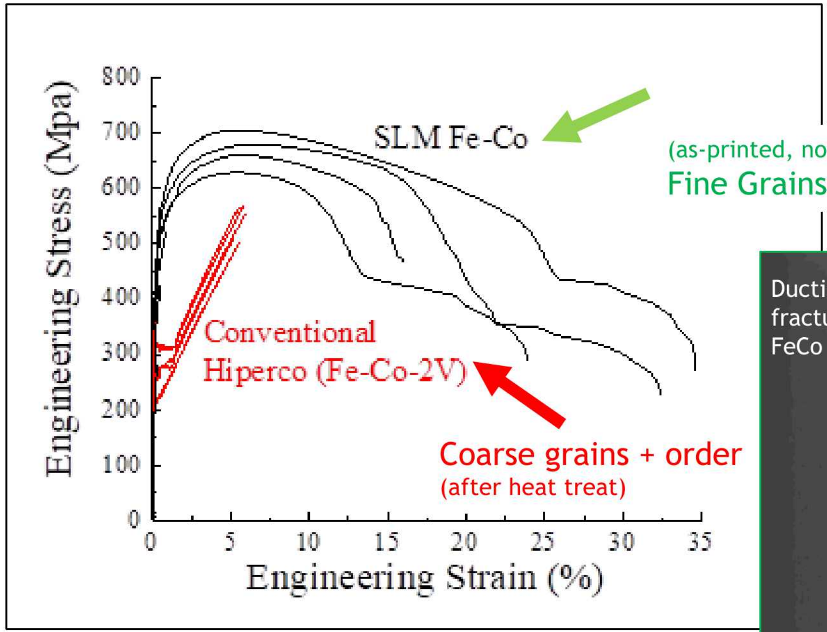


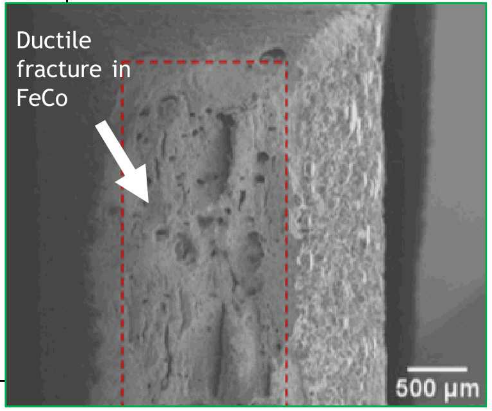
D. F. Susan, T. Jozaghi, I. Karaman, and J. M. Rodelas, *Journal of Materials Research,* vol. 33, no. 15, pp. 2168-2175, 2018.
D. F. Susan, I. Karaman, and T. Jozaghi, Dept. of Materials Science and Engineering Seminar, College Station, TX, USA, Oct. 17th, 2016.

Mechanical property improvement for FeCoV alloys can be realized using metal additive manufacturing (AM)

- The rapid solidification and cooling during metal AM results in structural refinement as can avoid the B2 ordering reaction in FeCo2V resulting in disordered bcc with ductile behavior
- Like ECAE, heat treatment to restore soft magnetic properties is expected to adversely affect mechanical property enhancement

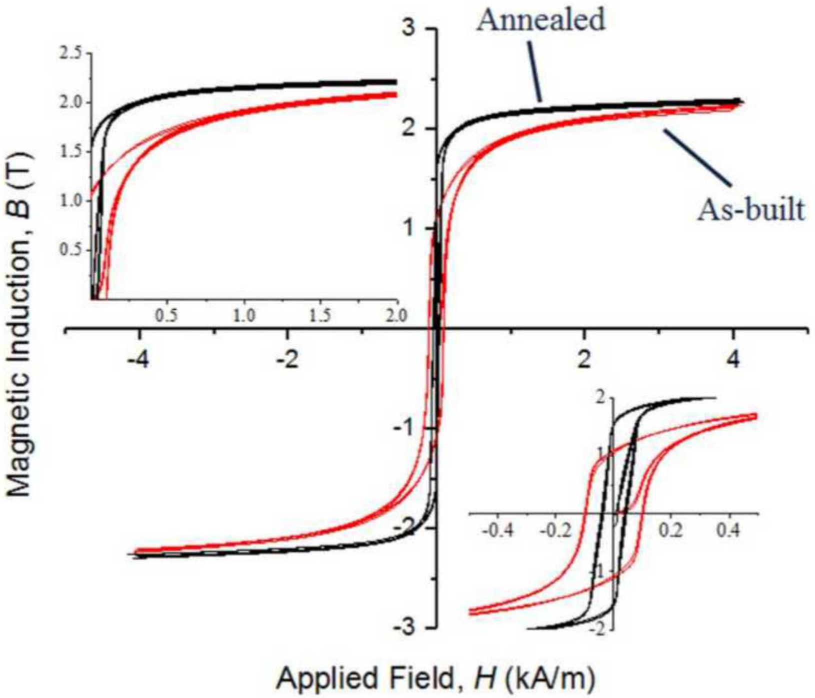
Mechanical Property Improvement of FeCo via AM PBF

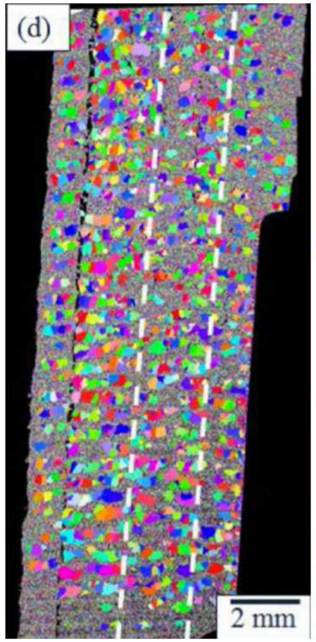




T. F. Babuska *et al.*, *Acta Materialia,* vol. 180, pp. 149-157, 2019/11/01/ 2019.

Magnetic Properties of FeCo1.5V not ideal as-AM DED





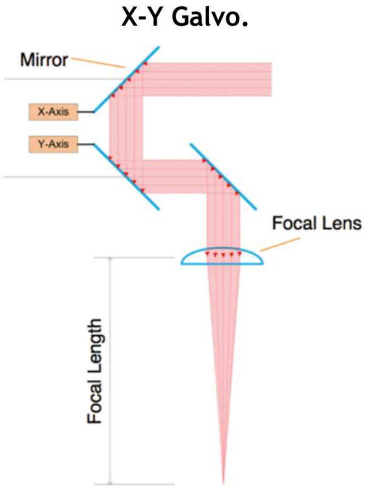
A. B. Kustas *et al.*, *Additive Manufacturing,* vol. 21, pp. 41-52, 2018/05/01/ 2018.

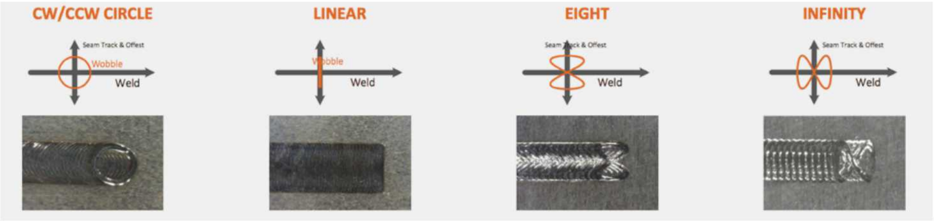
Can we develop a method to improve mechanical behavior without sacrificing bulk magnetic properties?

Laser welding ‘wobble’ system used to create AM-like structures on wrought heat-treated FeCo2V

- High-frequency galvanometrically controlled laser welding stations can create AM-like solidification growth rates and thermal histories

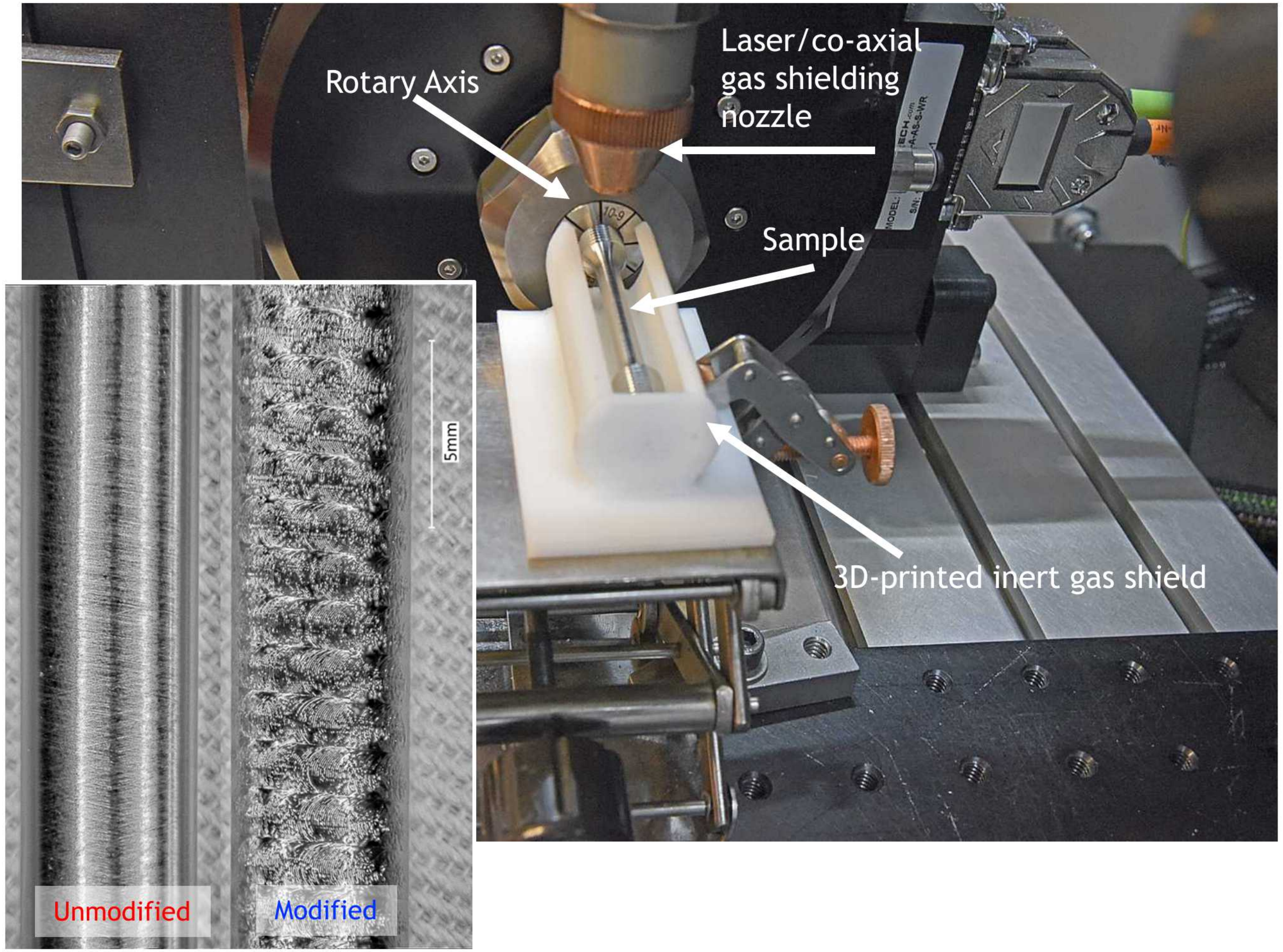
Wobble Laser Welding System





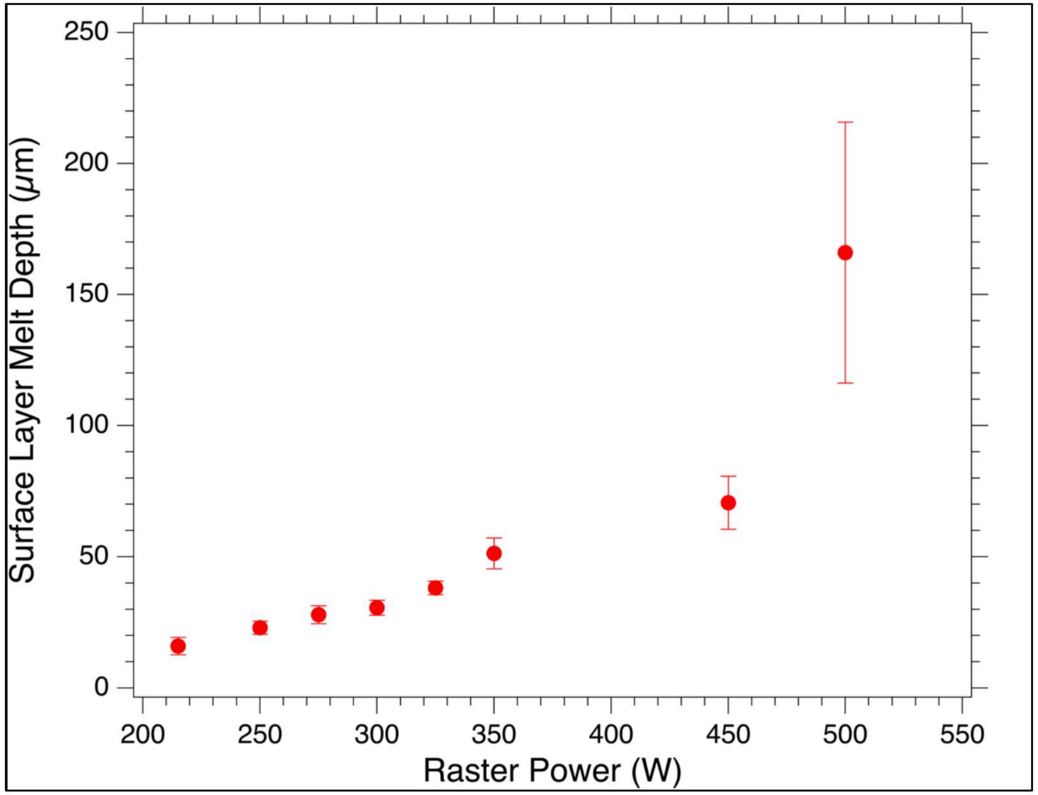
Wobble processing head allows beam oscillation up to 1 kHz

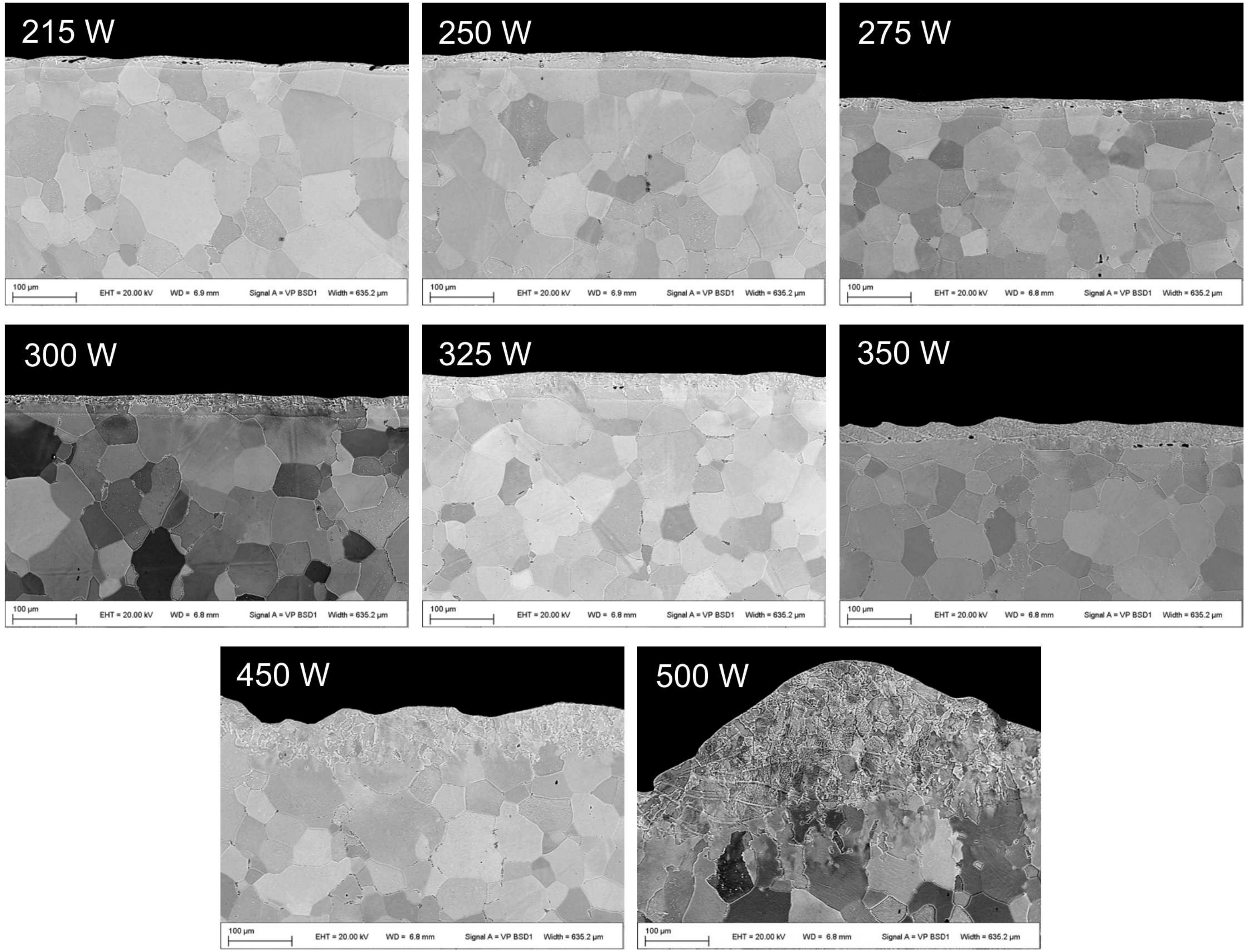
Laser Surface Modification Setup



Depth of laser processed layer varies with laser power

- Backscatter electron micrographs show increasing melt layer depth with applied laser power
- Surface height variations accompany higher power conditions (≥350 W)

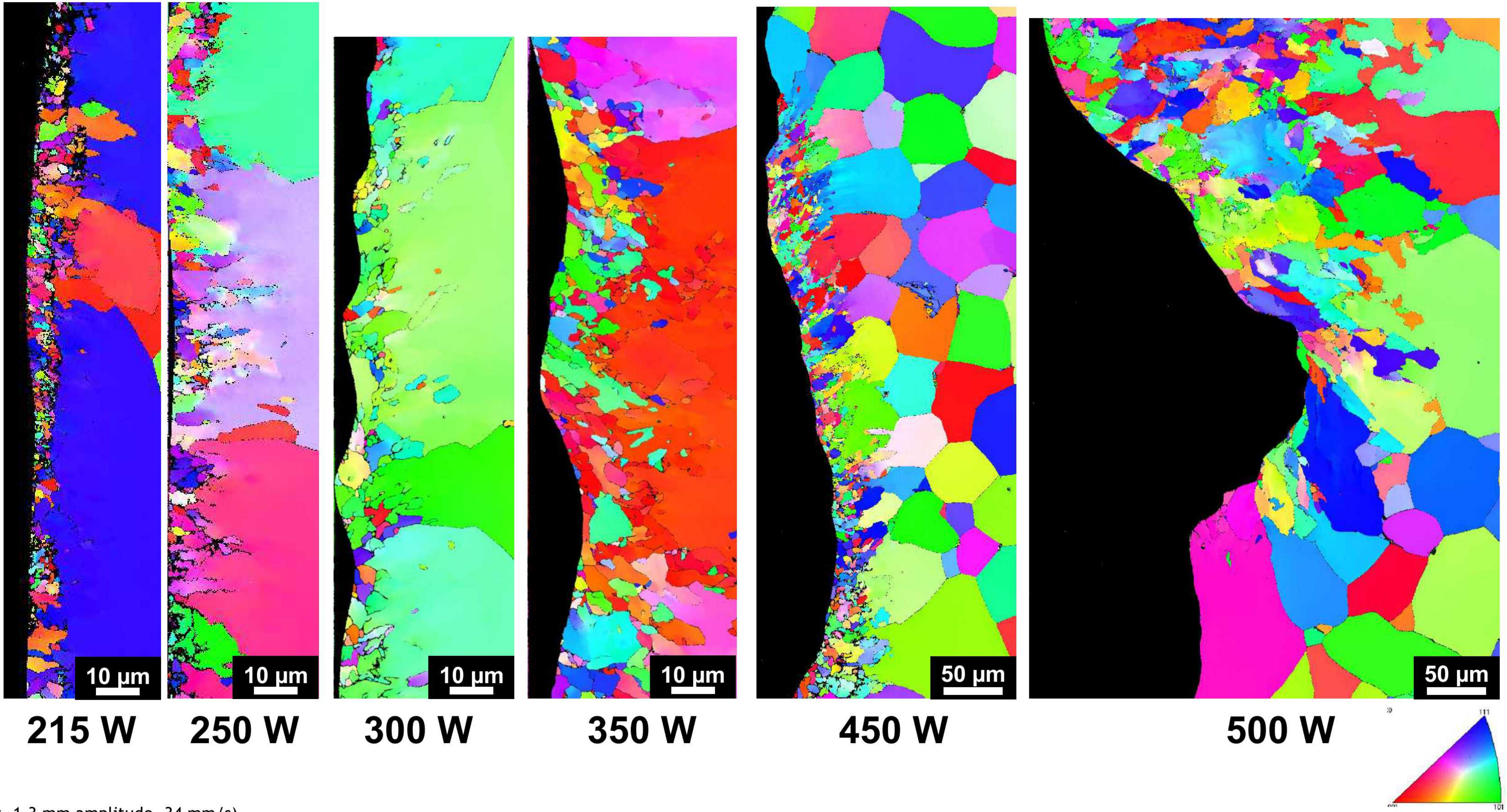




(CW Circle, 606 Hz, 1.3 mm amplitude, 34 mm/s)

Electron backscatter diffraction maps show grain refinement in laser surface modified layer

- Rapid solidification results in micron-scale solidification grains at the part surface

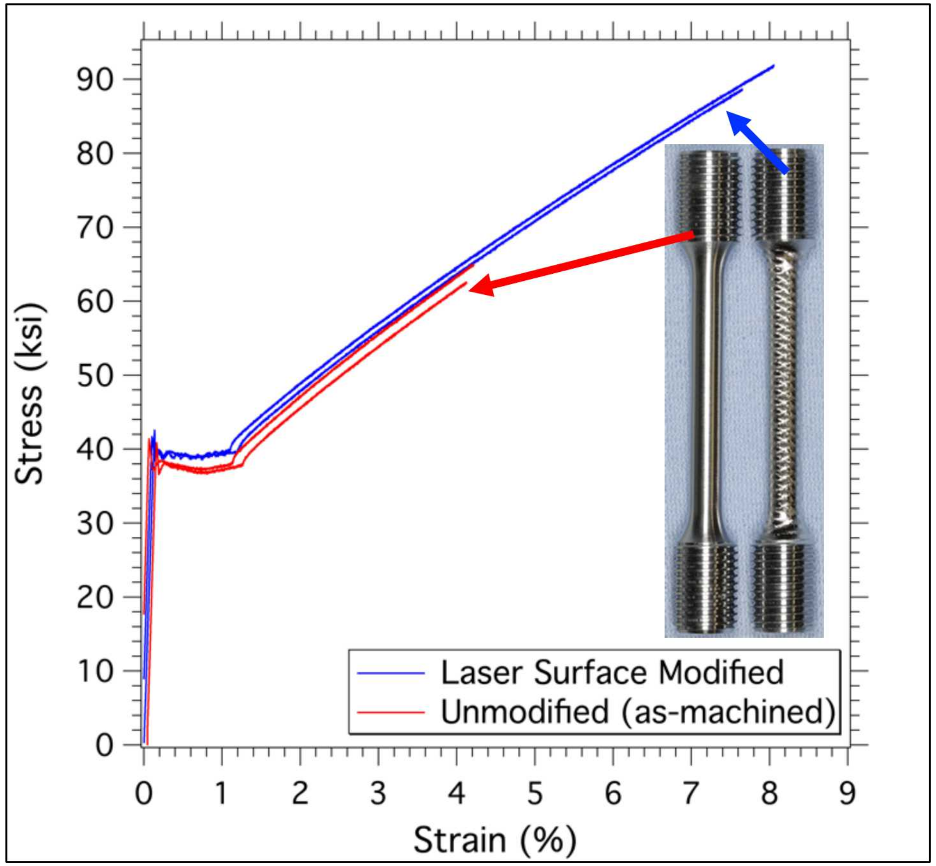


(CW Circle, 606 Hz, 1.3 mm amplitude, 34 mm/s)

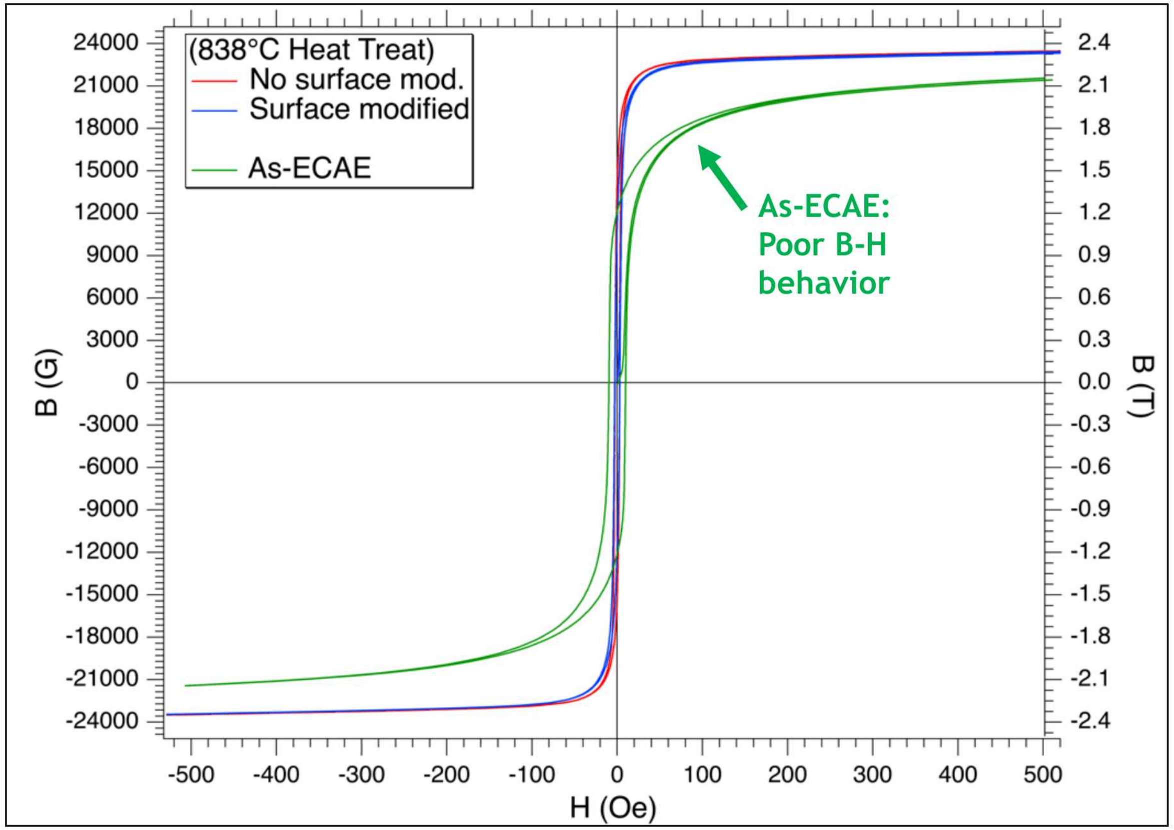
Site-specific laser surface processing offers tensile behavior improvement without impacting magnetic characteristics

- Tensile testing shows ~100% improvement in ductility and ~50% improvement in tensile strength
- Relatively small volume of processed material (~0.3 vol% for 250W condition) results in no significant degradation in measured B-H characteristics
- Surface modification circumvents the mechanical-magnetic property tradespace associated with traditional bulk methods used to improve Hiperco (e.g., ECAE or metal AM)

Tensile stress-strain



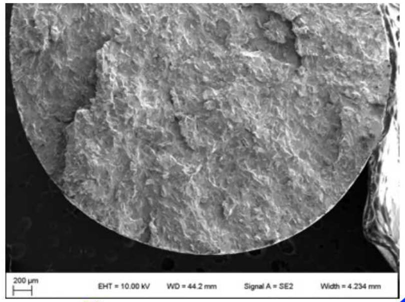
D-C B-H Loop

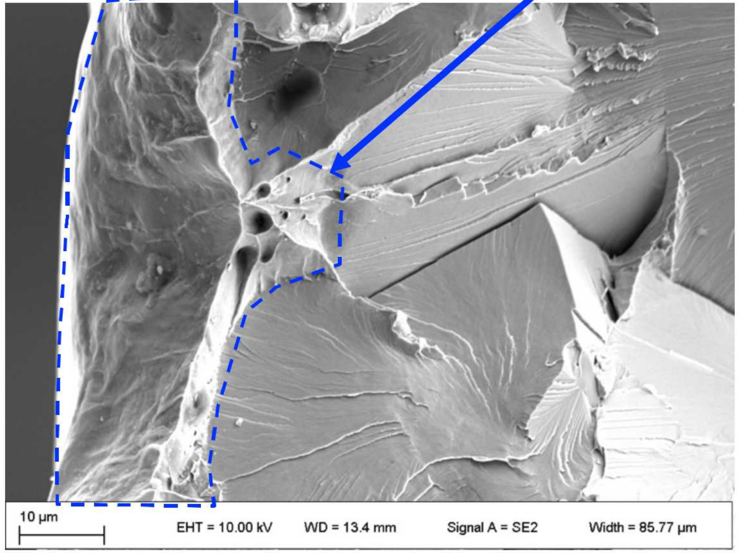


Fractographic examination of laser surface modified samples shows ductile fracture features

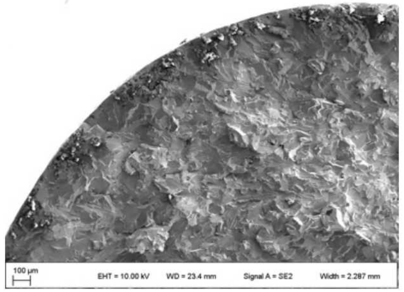
- Overall fracture for FeCo2V samples examined shows brittle cleavage fracture
- Surface modification resulted in locally ductile fracture features in FeCo2V. Ductile fracture features are only observed for disordered FeCo2V

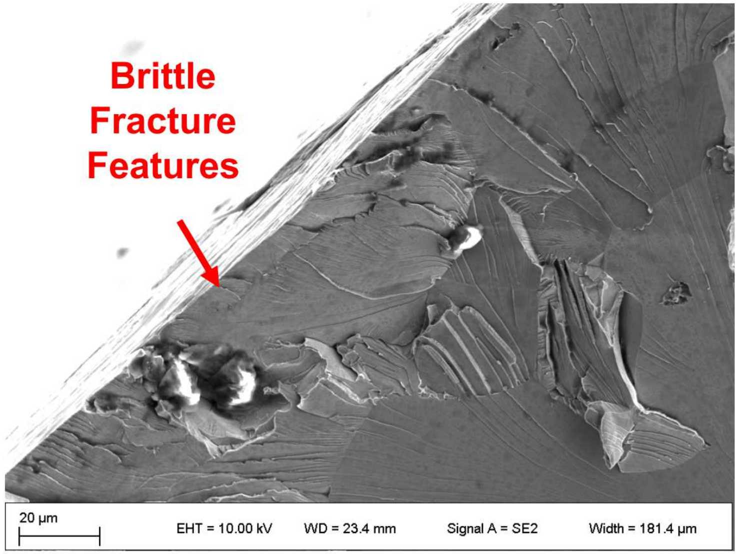
Surface Modified (250W)



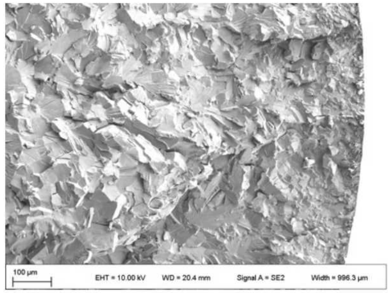


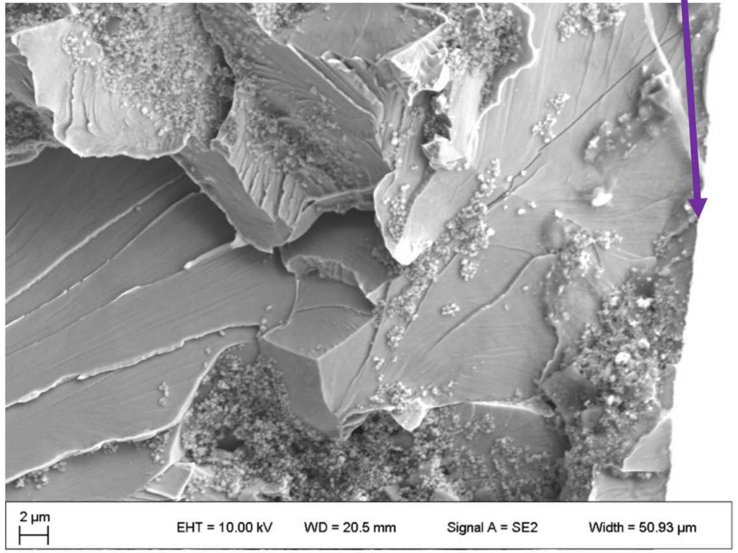
No Surface Mod.





Electron Beam Modified (~4X higher linear heat input)

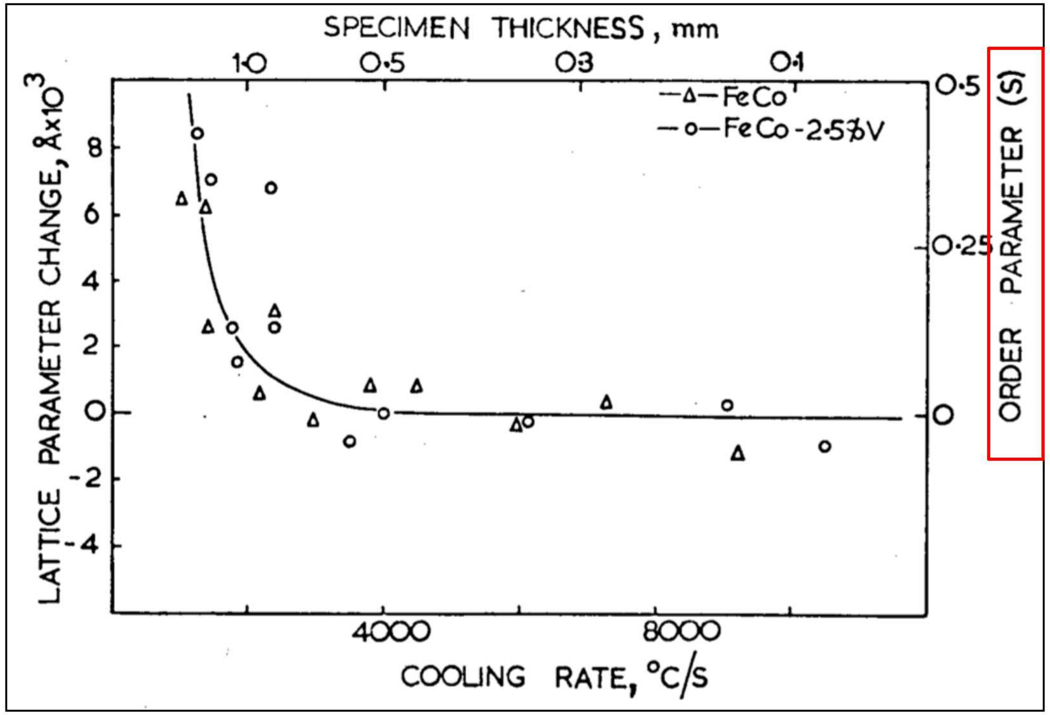


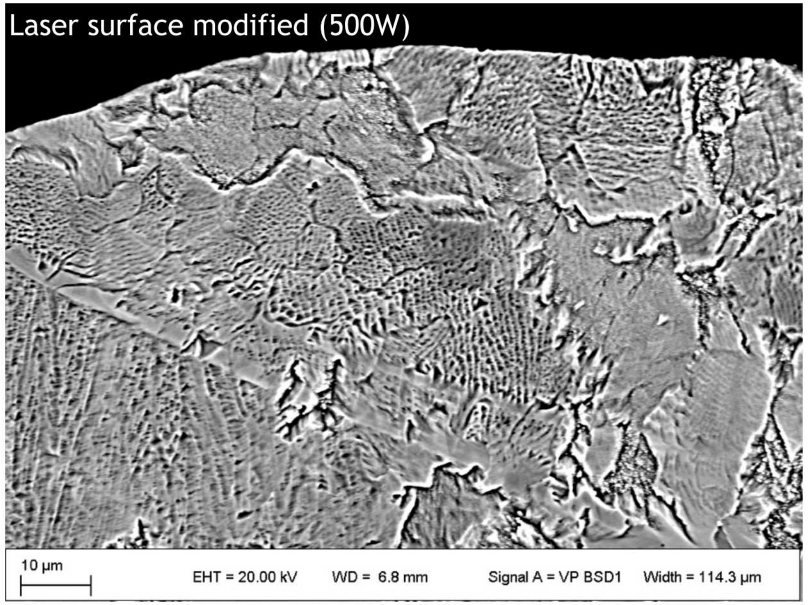


Rapid solidification and cooling generates disordered, fine-grained surface microstructures that preclude defect-initiated failure

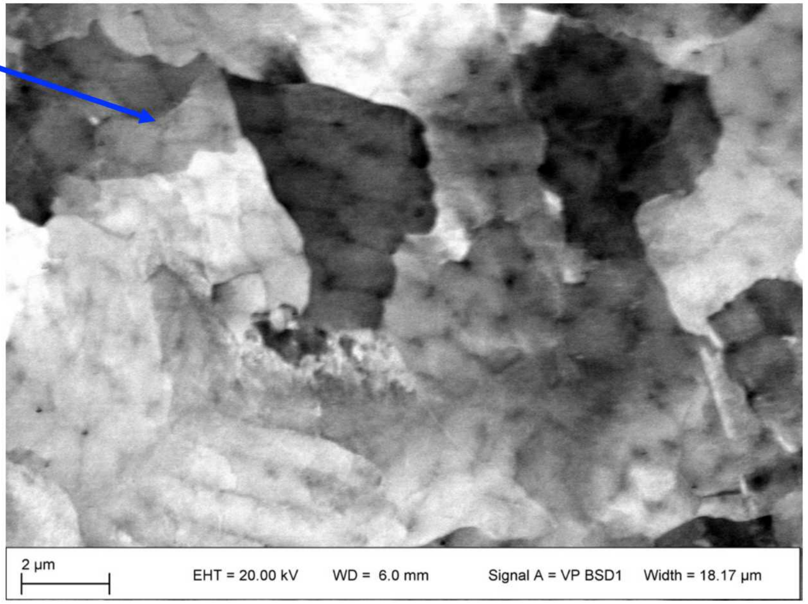
- If FeCo2V is cooled rapidly ($\geq 10^3$ °C/s), atomic ordering reaction is prevented
- Rapidly quenched FeCo2V will behave like a a disordered bcc-alloy (i.e., ductile, no notch sensitivity, necking prior to failure)

Atomic ordering of FeCo alloys can be avoided with rapid cooling





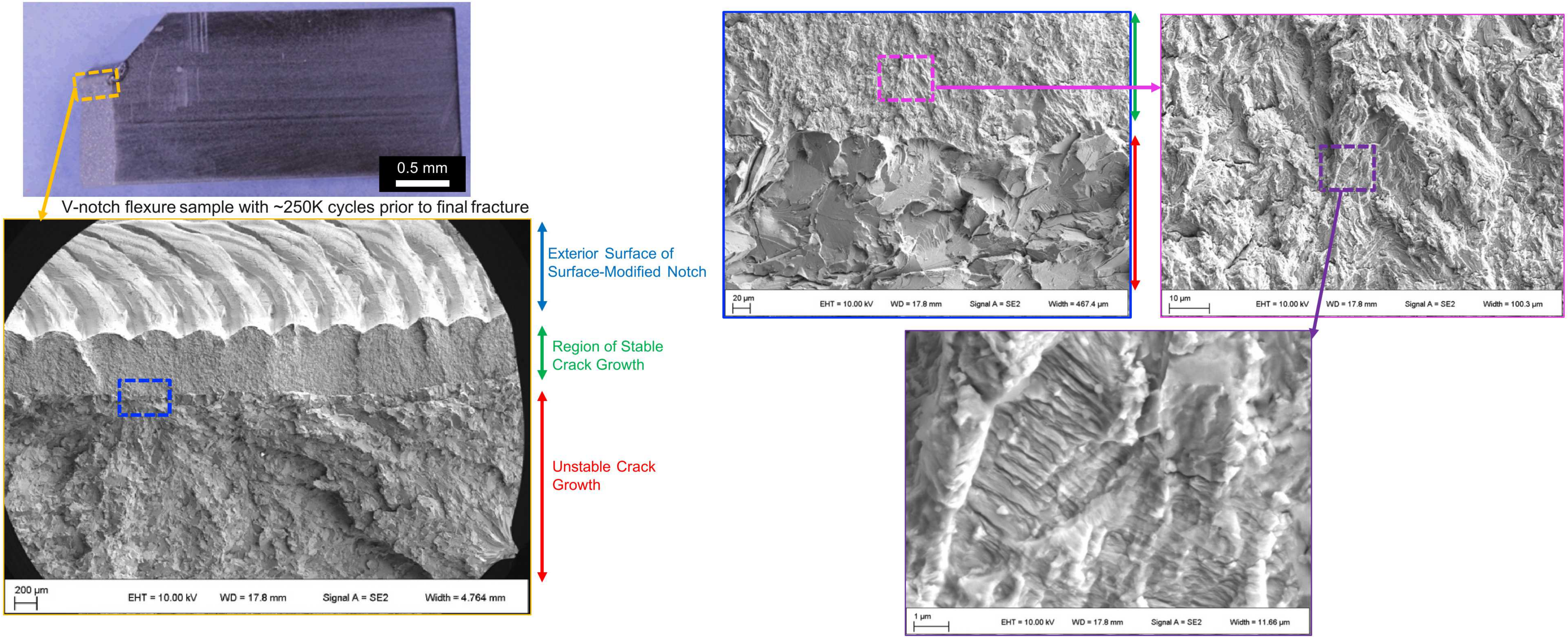
Cellular solidification substructure in rapidly solidified FeCo2V with estimated cooling $>10^3$ °C/sec.



D. W. Clegg and R. A. Buckley, *Metal Science Journal,* vol. 7, no. 1, pp. 48-54, 1973/01/01 1973.

The ability to create location-specific atomic disorder in FeCo2V addresses challenges with fracture behavior characterization

- Inability to reliably fatigue pre-crack FeCo2V has historically complicated the collection of valid K_{Ic} data
- Laser modified V-notch flexural samples show stable fatigue pre-crack on fracture surface.



Evidence of stable crack growth (fatigue)

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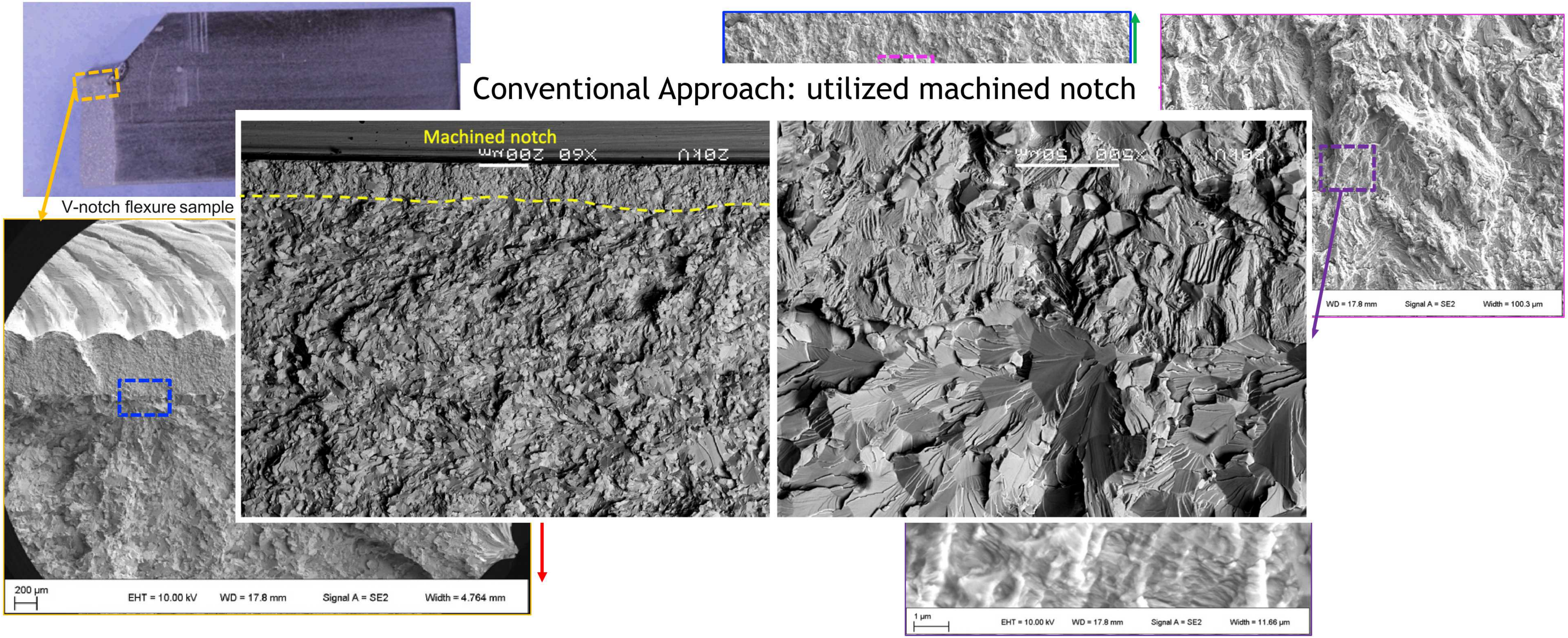

Evidence of stable crack growth (fatigue)

Conclusions

- Laser surface modification offers an alternative processing route to improve mechanical behavior of FeCo2V without accompanying degradation to soft magnetic behavior observed for bulk processing methods (e.g., ECAE or AM)

- ~100% improvement in ductility with ~50% increase in tensile strength observed without significant degradation to B-H characteristics

- Rapid solidification and cooling during laser surface melting results in grain refinement and circumvention of long-range atomic order
  - Laser surface melting was able to impart locally ductile fracture in FeCo2V

- The ability to impart local disorder in FeCo2V alloys can be leveraged to enable property measurements otherwise difficult when the material is fully ordered

On-going work

- Additional process parameter space development on 'wobble' system
- Developing the capability to laser process complex component geometries
- Application of laser surface modification methods to other ordered intermetallic soft magnetic alloys (ex. Fe-6Si)

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