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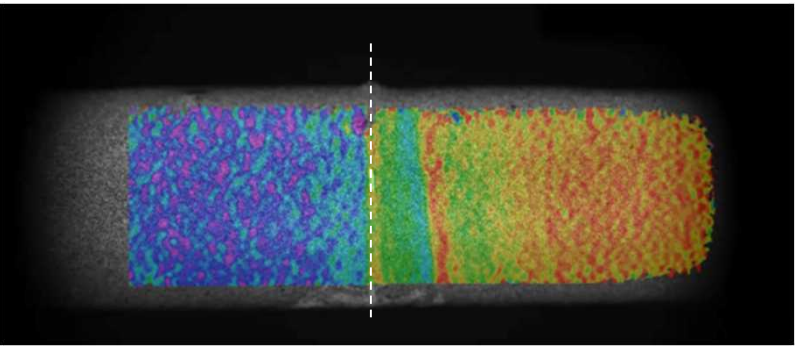

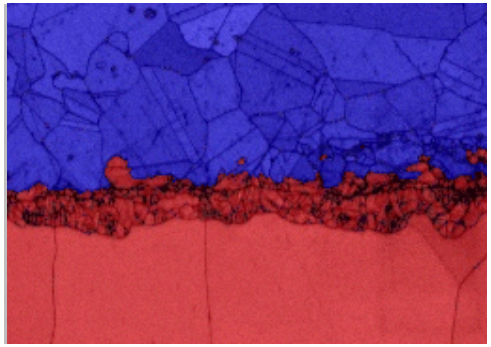

Solid State Welding of Fe-Co-V Soft Magnetic Alloys

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Sandia National Laboratories, Albuquerque NM

April 26th, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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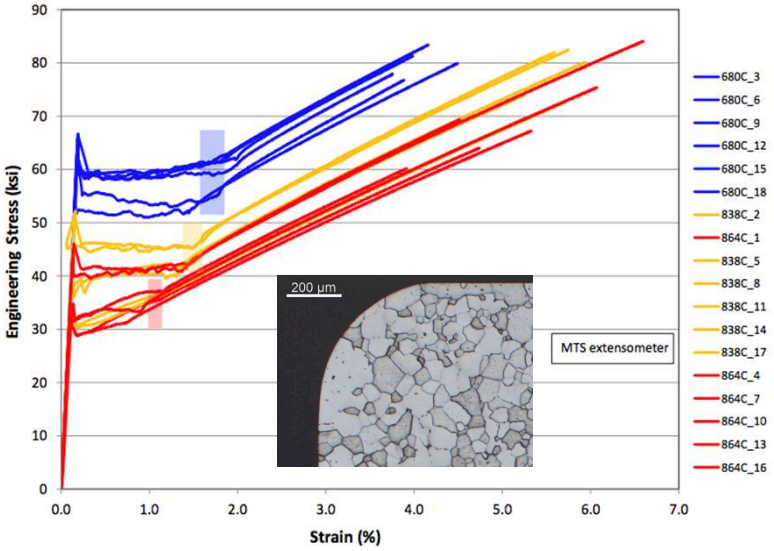
FeCo-V Soft Magnetic Alloy

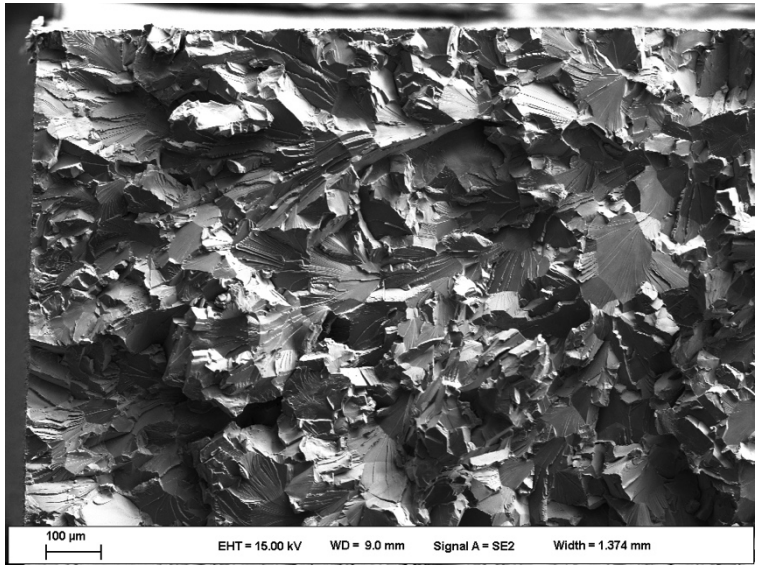
- Fe-49Co-2V (Hiperco® 50A, 2V Permendur) is an ordered soft magnetic material with the highest magnetic saturation of any material

- Hiperco is typically used for high-efficiency solenoids, motors, transformer cores, etc.

- While magnetic properties are ideal, strength, ductility, and fusion weldability are regarded as poor



Generally low elongation to failure for Hiperco bar



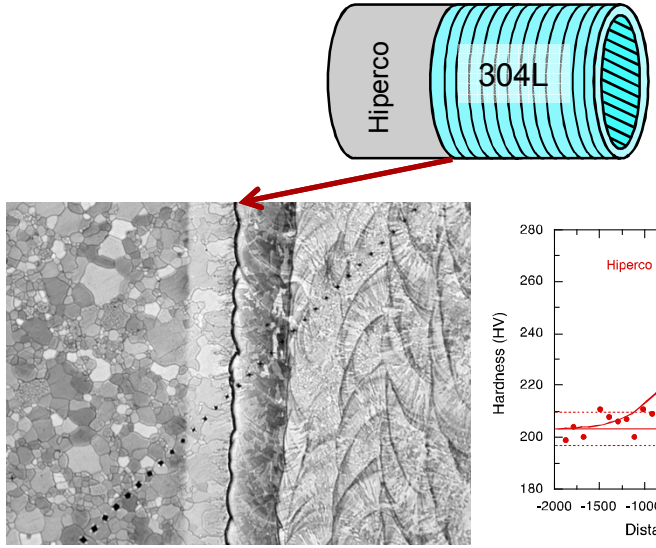
Mechanical failure results with no necking and accompanying microscopic brittle features

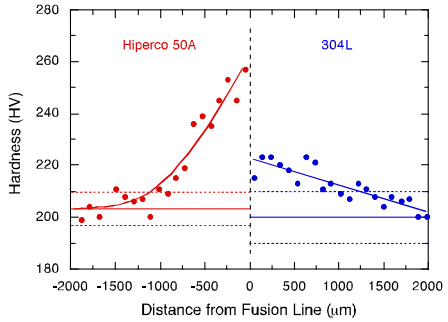
Motivation and Approach

- Evaluate <u>solid state</u> welding technique to join Hiperco to non-magnetic structural alloys to enable new design possibilities in severe mechanical environments
- Hot ductility measurements show >75% RA for T> 600° C
- Friction welding will be explored to create dissimilar solid state welds for 304L stainless steel to Hiperco 50A
  - Weld microstructure, post-weld heat treatments response, and local mechanical response will be characterized

- Highly damage tolerant
- Weldable via fusion welding processes

- Magnetic behavior only where needed



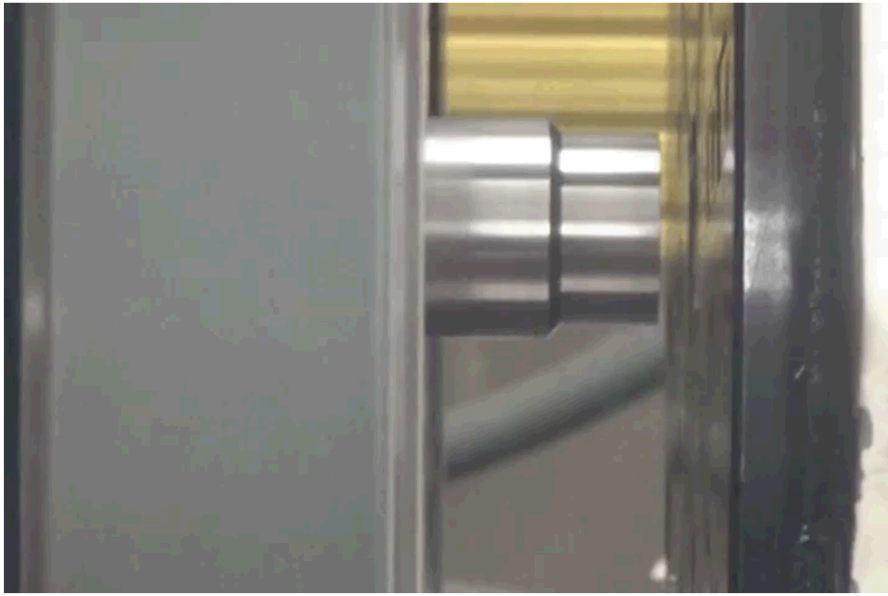


- Puskar et al. demonstrated directed energy deposition can be used to build 304L onto Hiperco
- Low ductility (0.1-1.3 %RA) was measured for dissimilar mechanical test samples

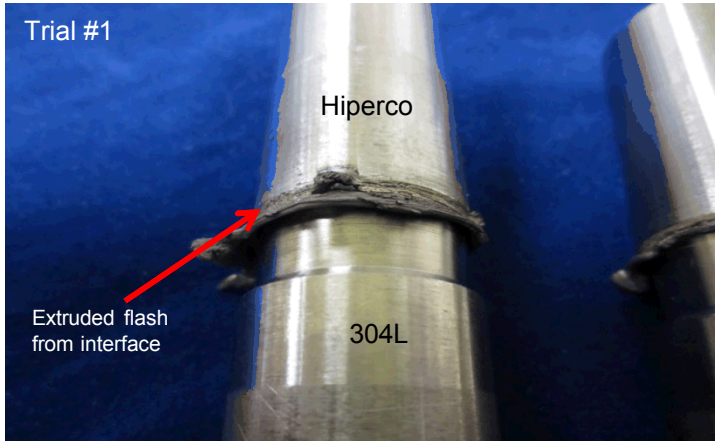
Puskar, J.D., Robino C.V., Oliver M.S., Brooks, J.A., Vanecek, C.W., Fabrication of Hiperco Alloy 50/304L Stainless Steel Structures. American Welding Society Meeting. May 9th, 2001.

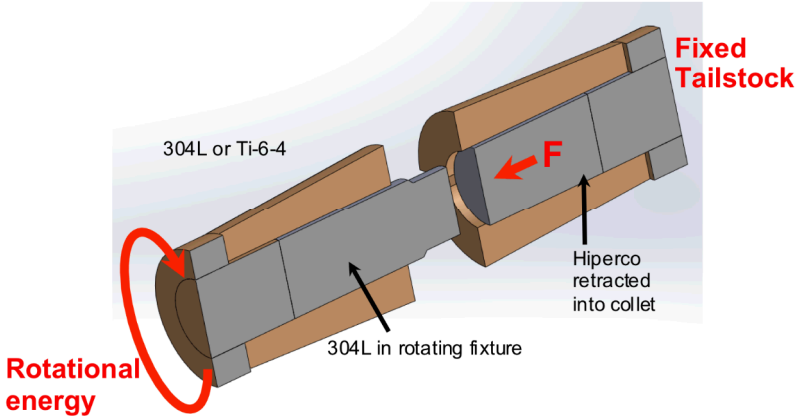
Solid State Joining via Friction Inertia Welding

- Solid state metallurgical bond created by elevated-temperature deformation resulting from frictional heating of impinging workpieces



(video)

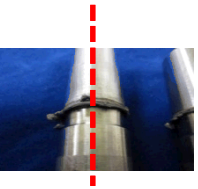




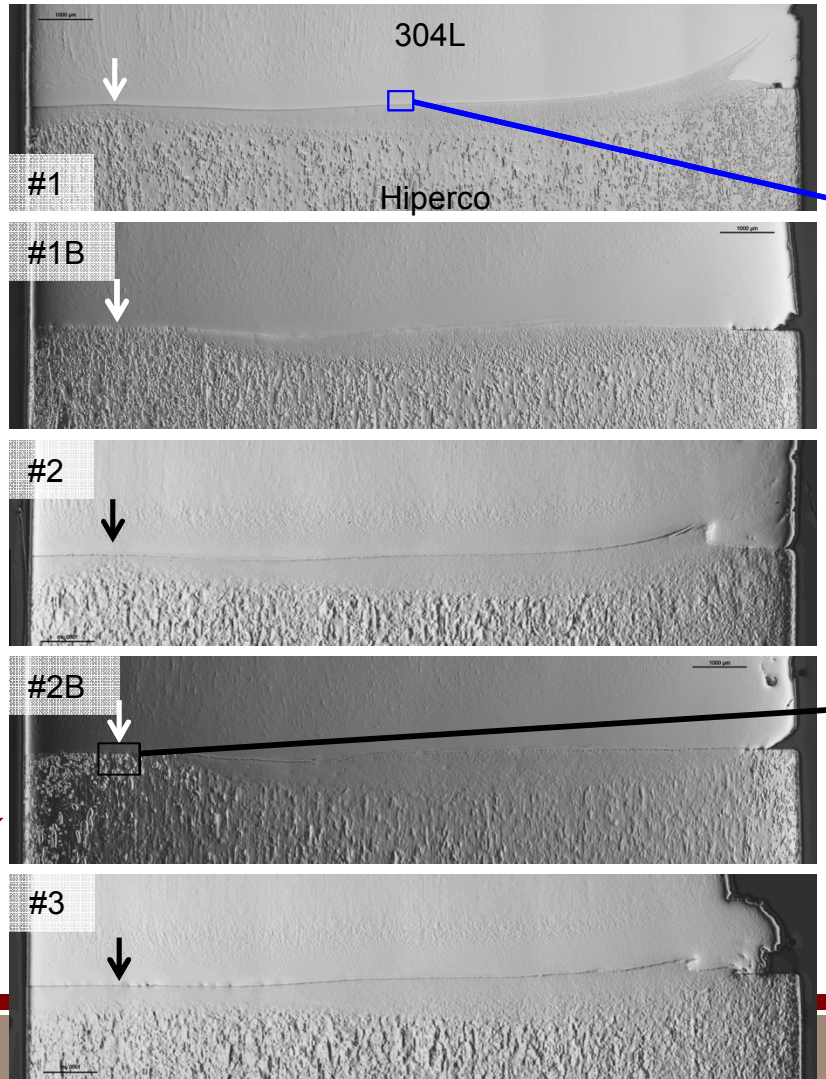
Schematic of inertia weld setup

304L/Hiperco Inertia Weld Trials

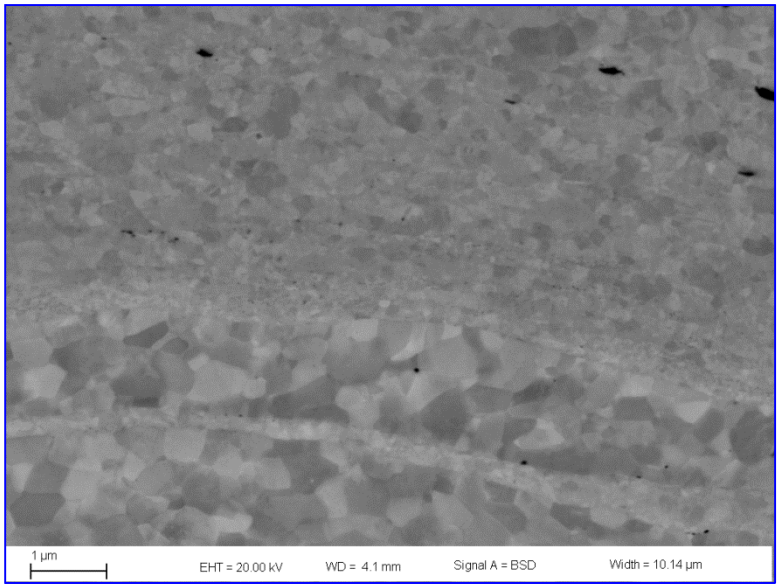
- Weld zone at original interface shows sub-micron dynamically recrystallized grains



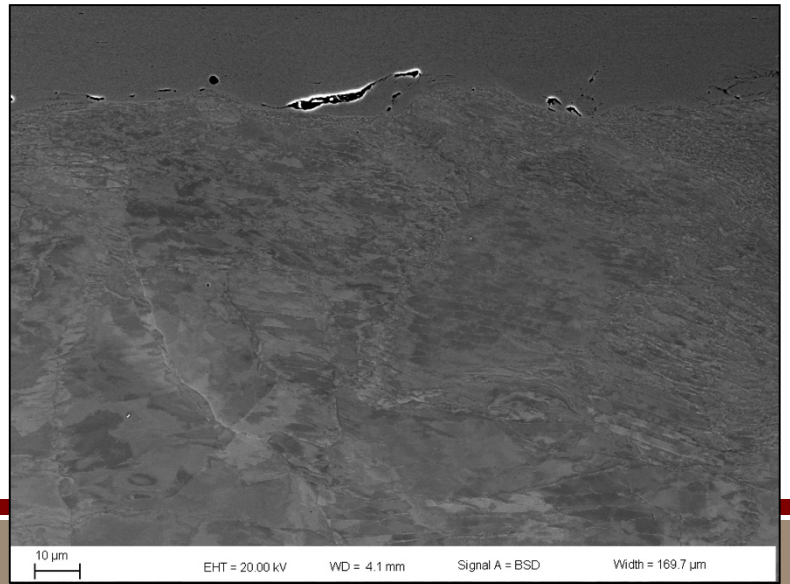
Transverse cross section of inertia weld sample



Weld Zone



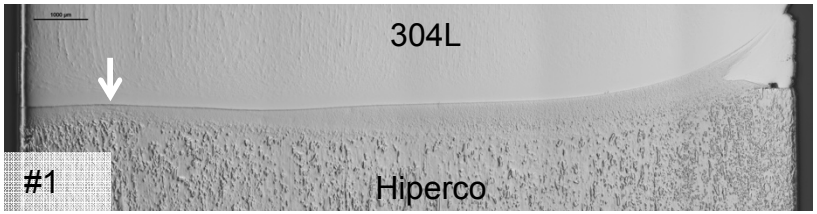
Sample Center



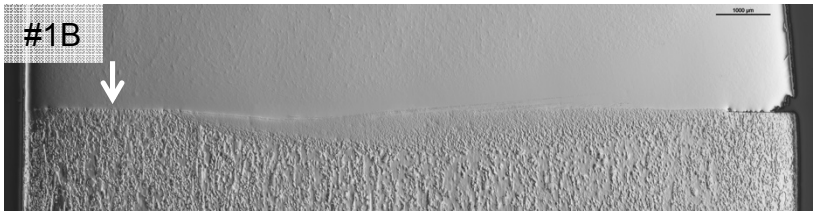
Two-Stage Welds Exhibit Improved Material Mixing

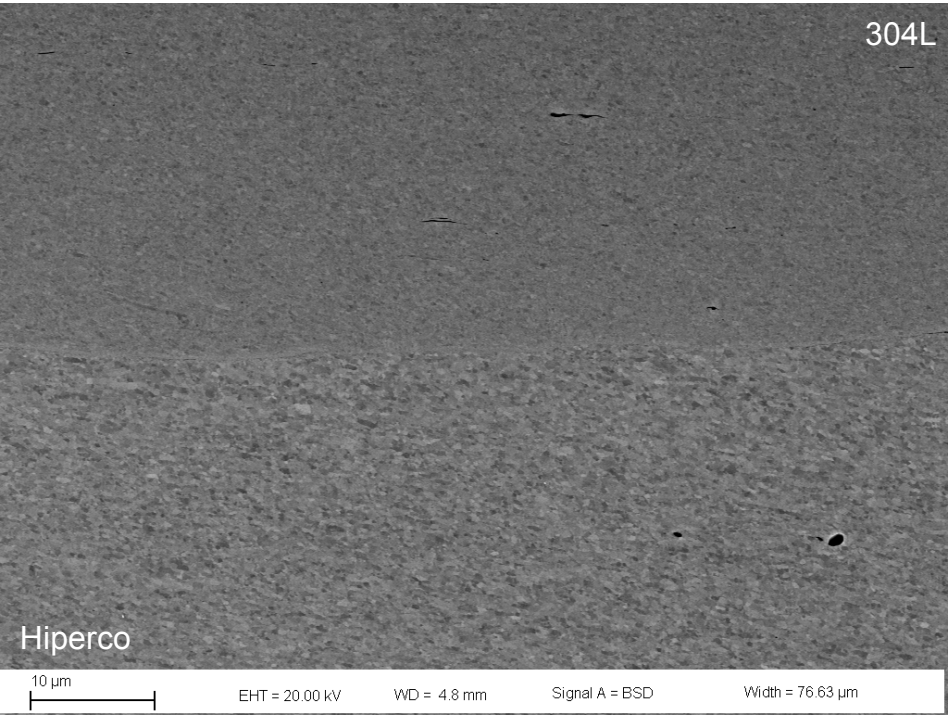
- Additional heating prior to final upset in two-stage inertia welds results in more tortuous weld interface

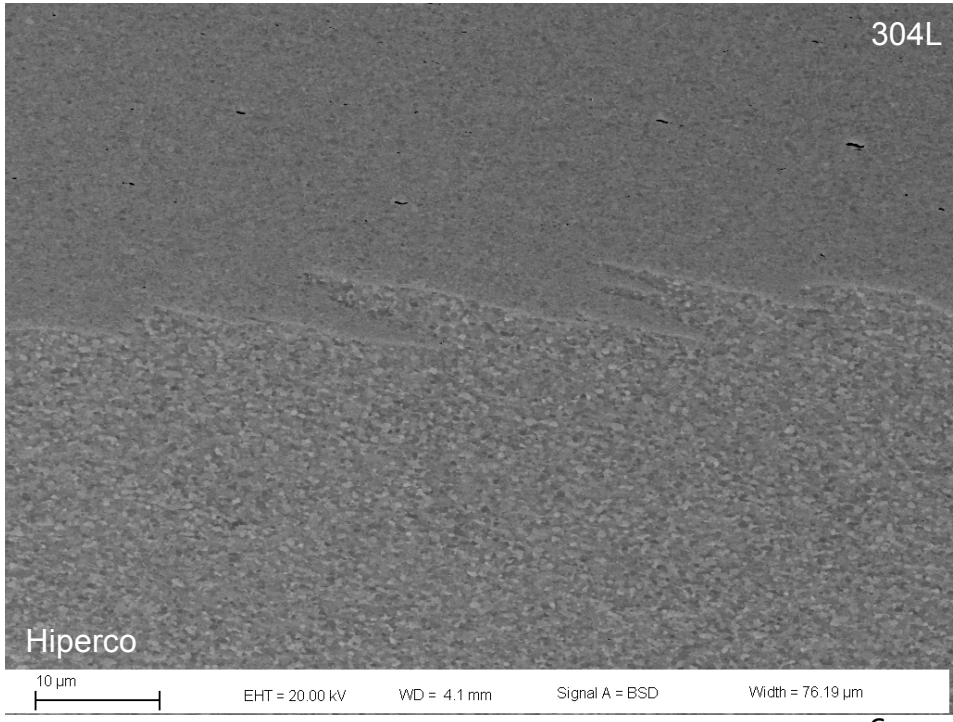
Single Stage



Two Stage



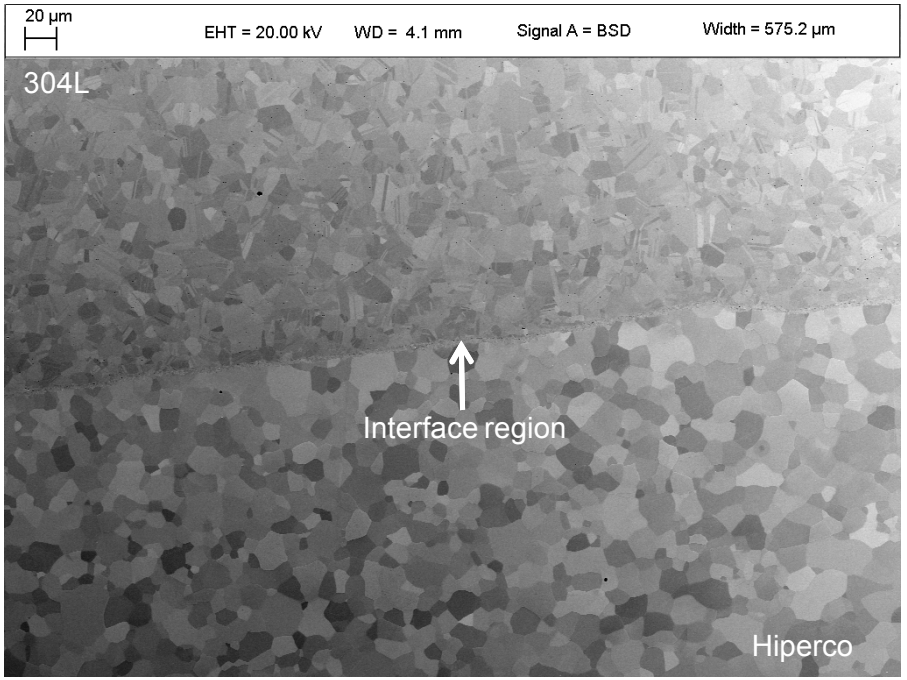




Heat Treatment Results in Weld Zone Coarsening

- Post-weld heat treatment to restore magnetic properties for Hiperco results in grain growth within weld region
  - No abnormal grain growth observed
- After heat magnetic heat treatment, a narrow (~2-3 µm wide) extremely fine-grained interfacial region persists

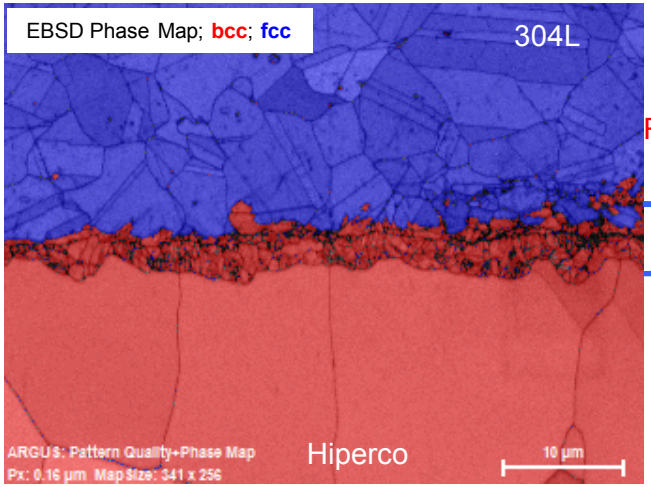
As-welded: 2-stage, #1B



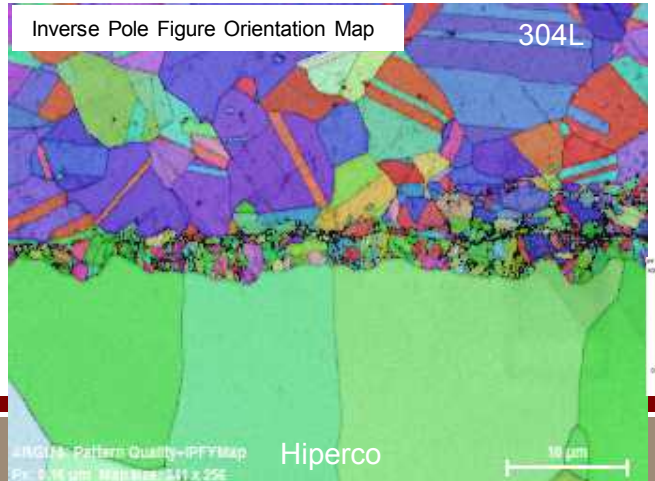
Magnetic HT: 838°C, 2hr.; #1B

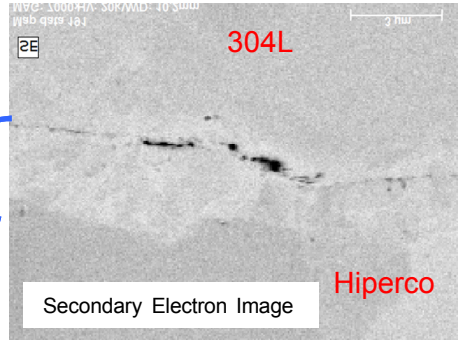
Vanadium Enrichment Within Reaction Layer

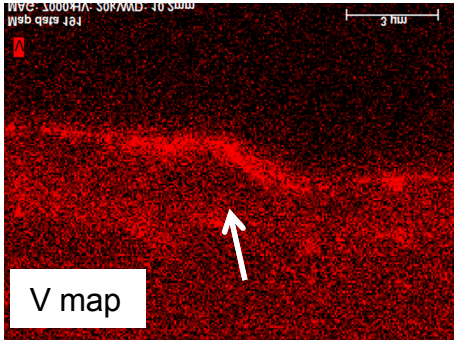
- Electron backscatter diffraction indicates fine-grained region has bcc crystal structure and is preferentially rich in Vanadium
- EDS shows evidence of interdiffusion within reaction layer

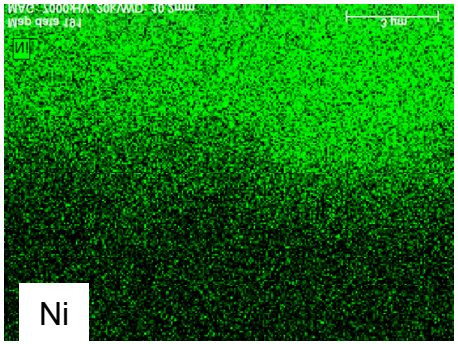


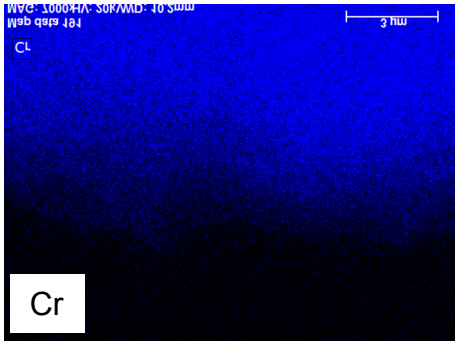
Reaction Layer

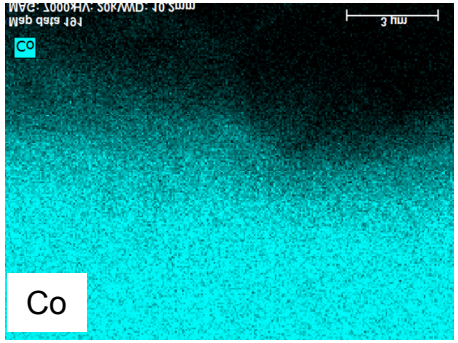


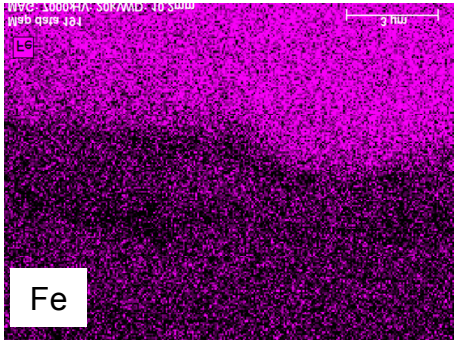






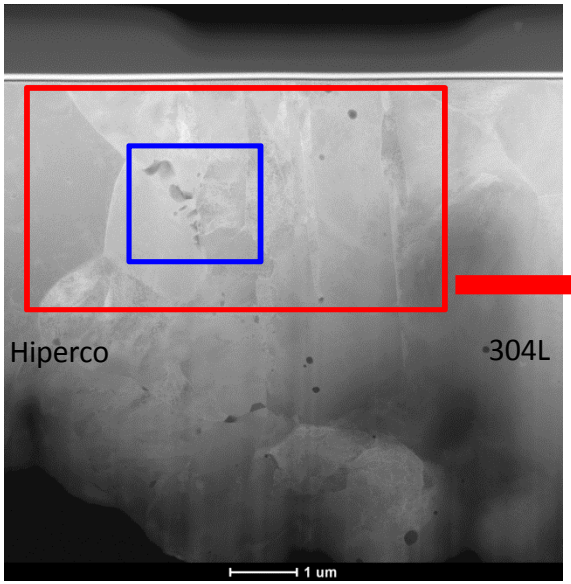


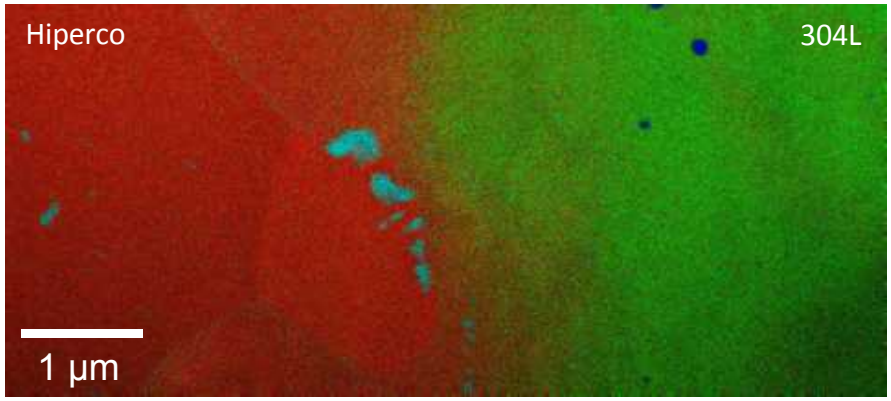


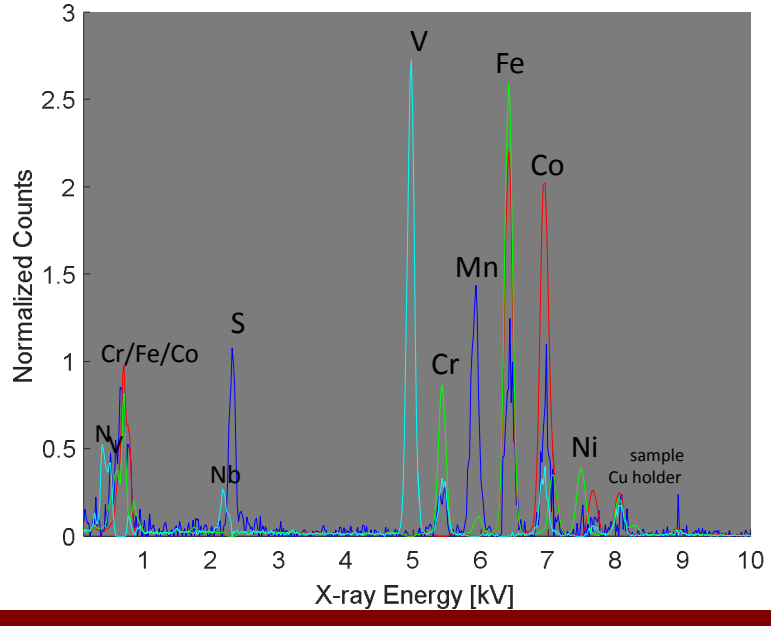


Reaction Layer Shows V-rich Nitrides after Heat Treatment

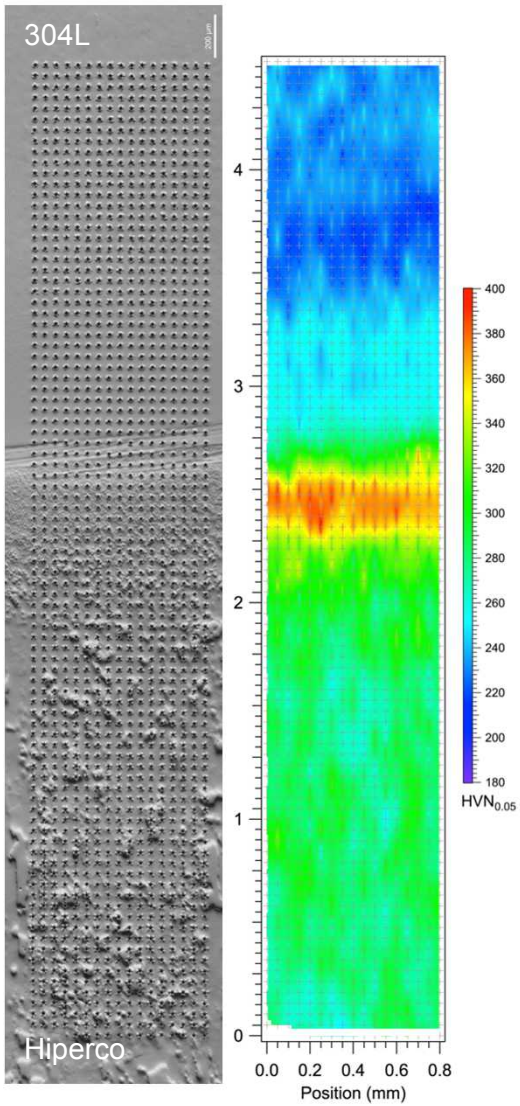
- High resolution TEM-EDS shows sub-micron particles are V-rich (V,Nb)N



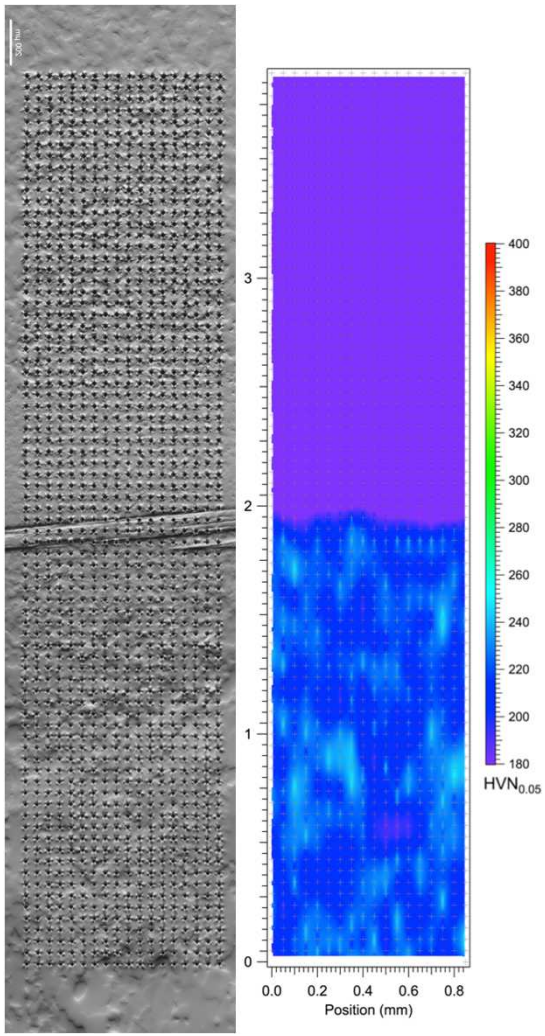




Microhardness Mapping Used to Assess Weld Zone Mechanical Properties



As-welded: 2-stage, #1B

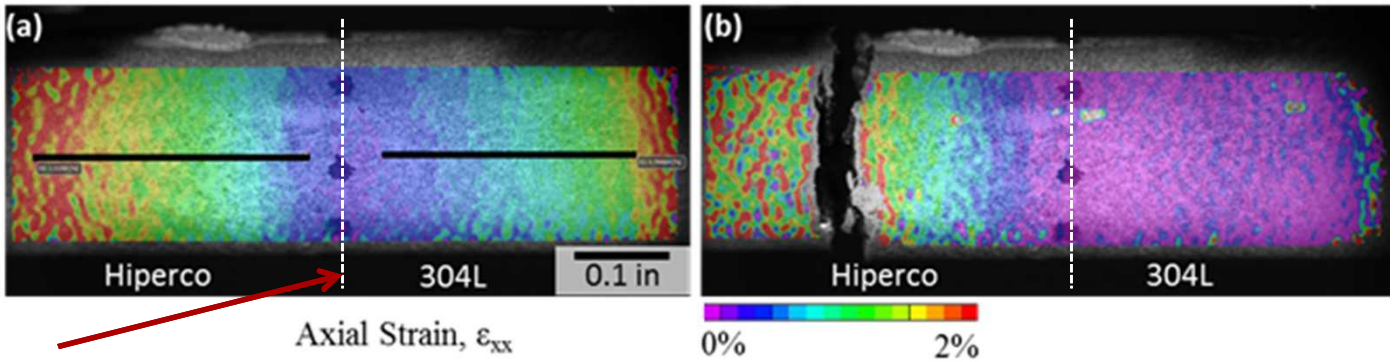


Magnetic HT: 838ºC, 2hr.; #1B

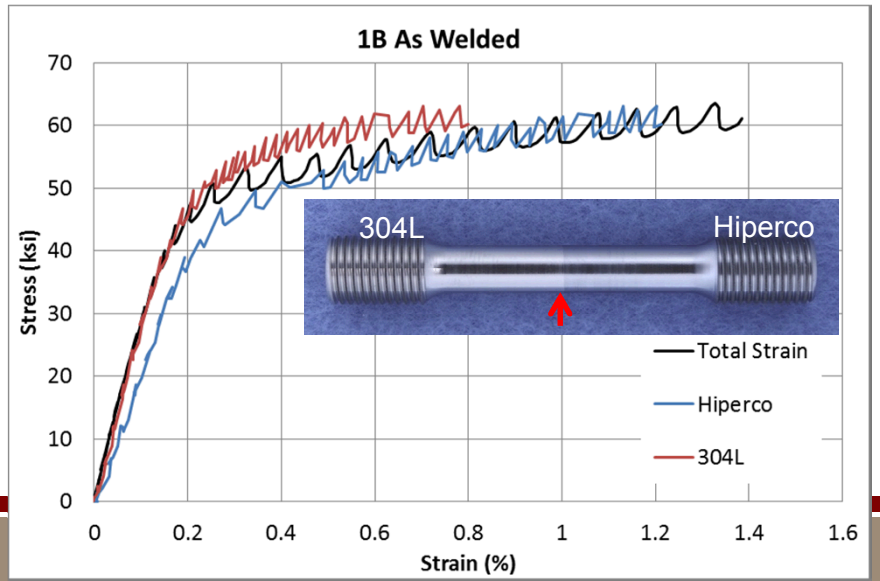
- Fine dynamically recrystallized grains in weld zone as-welded result in apparent strengthening near the original interface
  - ~200 HV gradient as-welded
- Static recrystallization/grain growth operative during post-weld heat treatment reduces gradient in hardness between 304L/Hiperco
  - ~60 HV gradient
- Any effects from thin (2-3 µm) reaction layer were missed by microhardness indents

Mechanical Testing of As-Welded 304L/Hiperco Reveals Brittle Failure in Hiperco away from Weld

- Strain concentrates in Hiperco away from weld zone
  - Hiperco without magnetic heat treatment (i.e., disordered) has poor ductility (1-3% strain to failure)
- Fracture occurs in Hiperco remote from weld zone

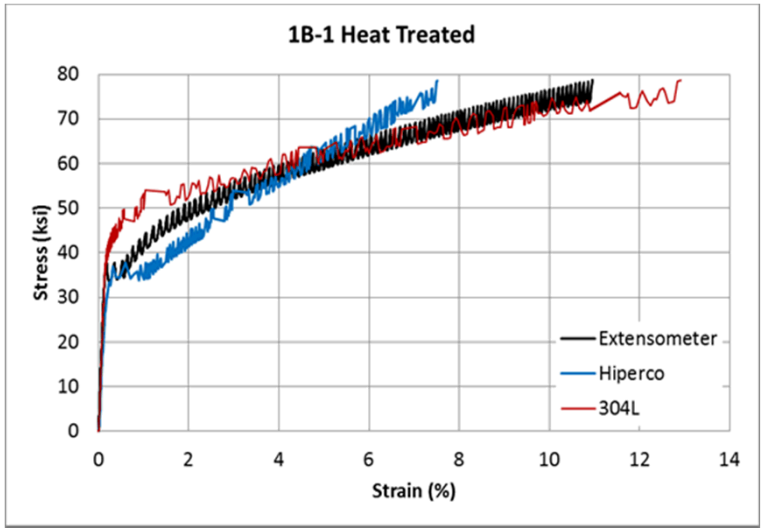


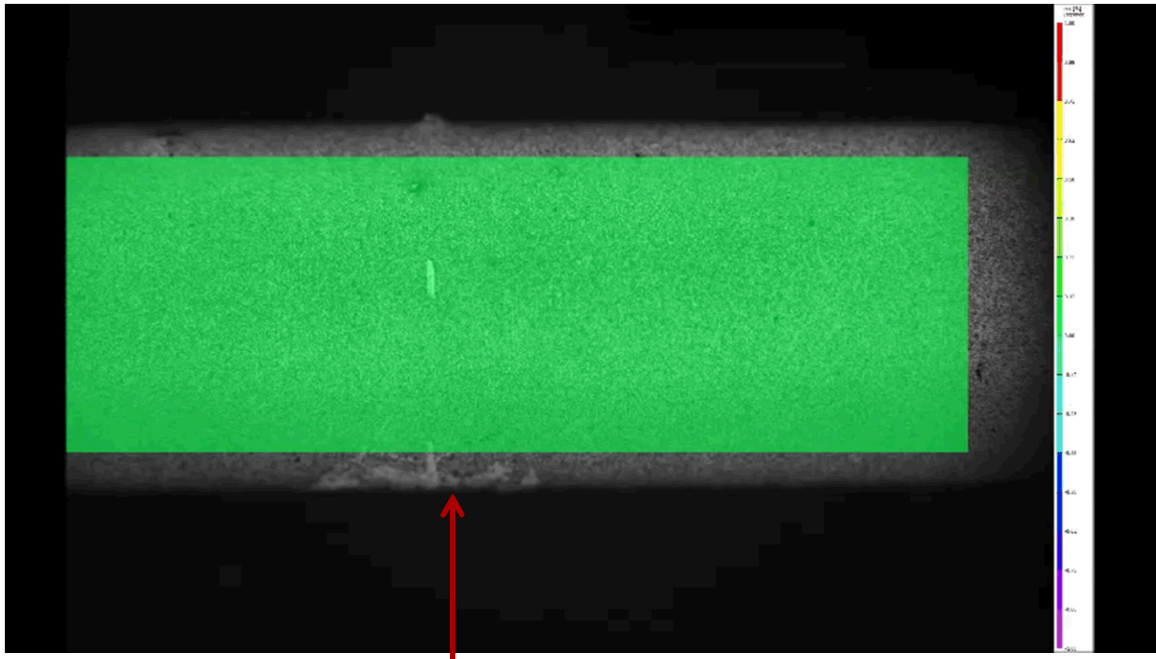
Weld Interface



Post-Weld Heat Treatment Results in Improved Inertia Weld Mechanical Behavior

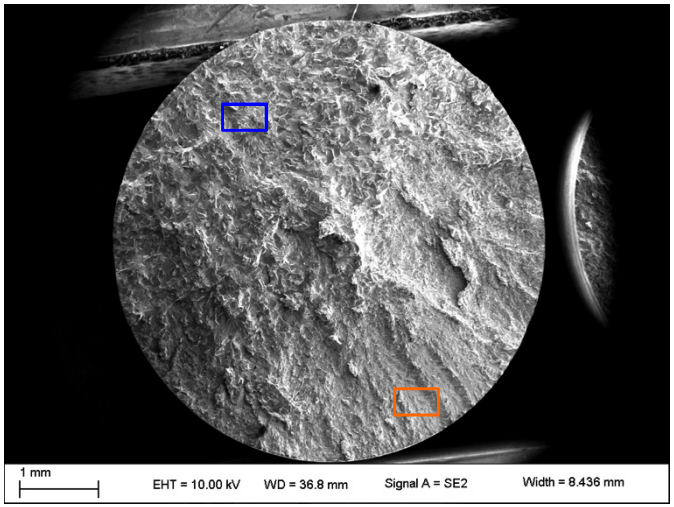
- Despite ordering reaction in Hiperco resulting from PWHT, advantageous mechanical behavior observed—11% global strain to failure.
- DIC movie shows plastic strain transfer from Hiperco to 304L resulting in overall increase in strain-to-failure relative to Hiperco alone

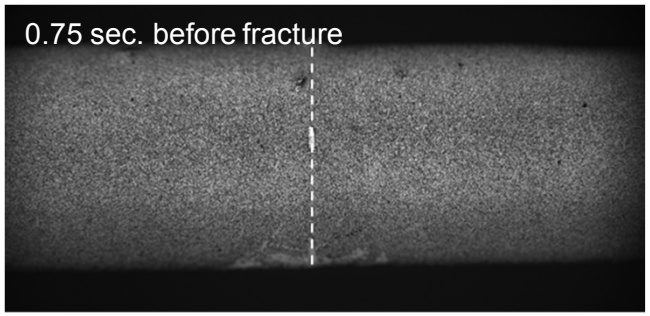


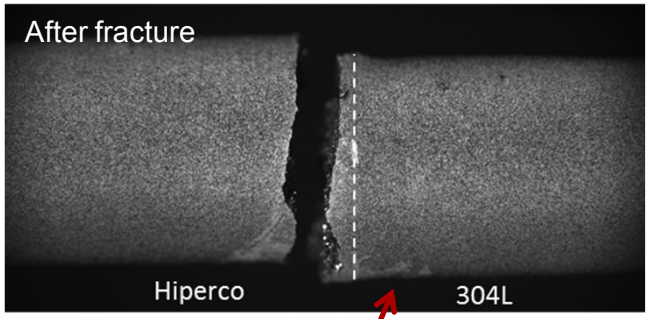


Fractographic Analysis

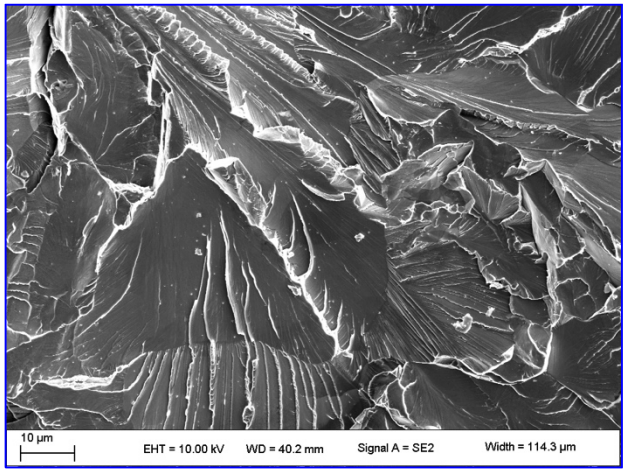
- Despite macroscopic ductile behavior measured via DIC, final fracture in Hiperco occurred via brittle transgranular cleavage

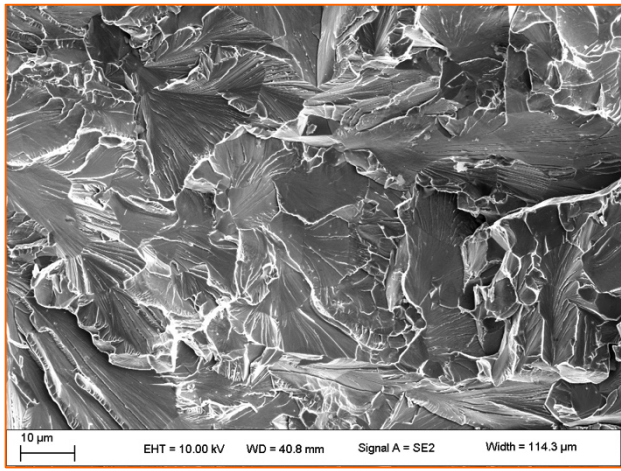






Cross sectional area reduction in 304L





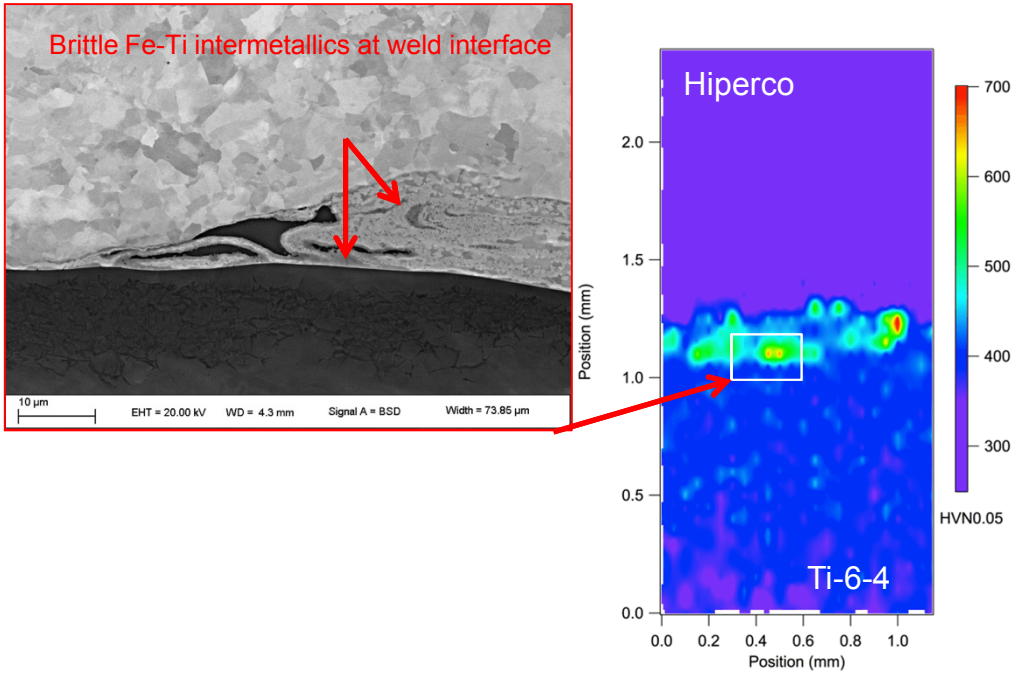
Conclusions

- Friction inertia welding demonstrated as robust method for dissimilar welding of 304L to Fe-Co-V (Hiperco)
- Two-stage weld cycle results in improved interfacial material mixing
- Post-weld heat treatment to restore Hiperco magnetic properties coarsens grains, reduces mechanical property gradient, and results in advantageous composite mechanical behavior
- Improved strain-to-failure of 304L/Hiperco bi-material samples can improve performance of electromagnetic assemblies in severe mechanical environments
  - Inertia welded 304L/Hiperco opens new design possibilities

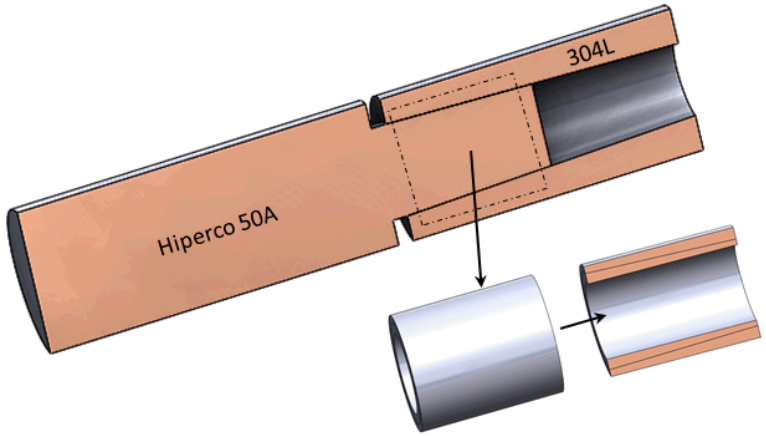
On-Going Work

- Continuation of 304L/Hiperco mechanical testing
- Ti-6Al-4V/Hiperco inertia weld sample characterization
- Concentric inertia welded bi-material samples

Ti-6Al-4V/Hiperco Welds Show Intermetallic Formation



Sample Design for co-axial Hiperco/304L blanks



Acknowledgements

- Special thanks to:
  - Charlie Robino
  - Alice Kilgo
  - Bonnie McKenzie
  - Mason Winters
  - Mark Reece

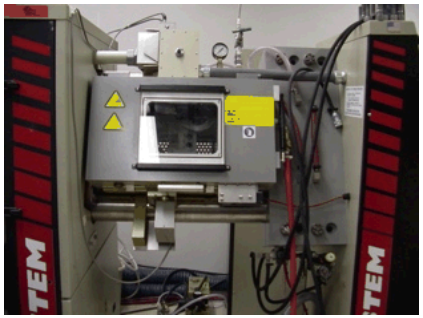
Backup Slides

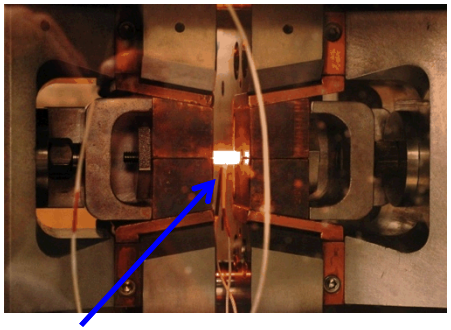
Sandia National Laboratories

Hiperco 50A Hot Ductility

- Gleeble 3500 Thermomechanical Simulator used to assess elevated temperature ductility/strength of Hiperco
  - Useful for determining feasibility of alloy to solid state welding such as inertia welding
- Hiperco shows considerable ductility if temperature >600ºC
  - Room temperature ductility for Hiperco 50A typically <10%

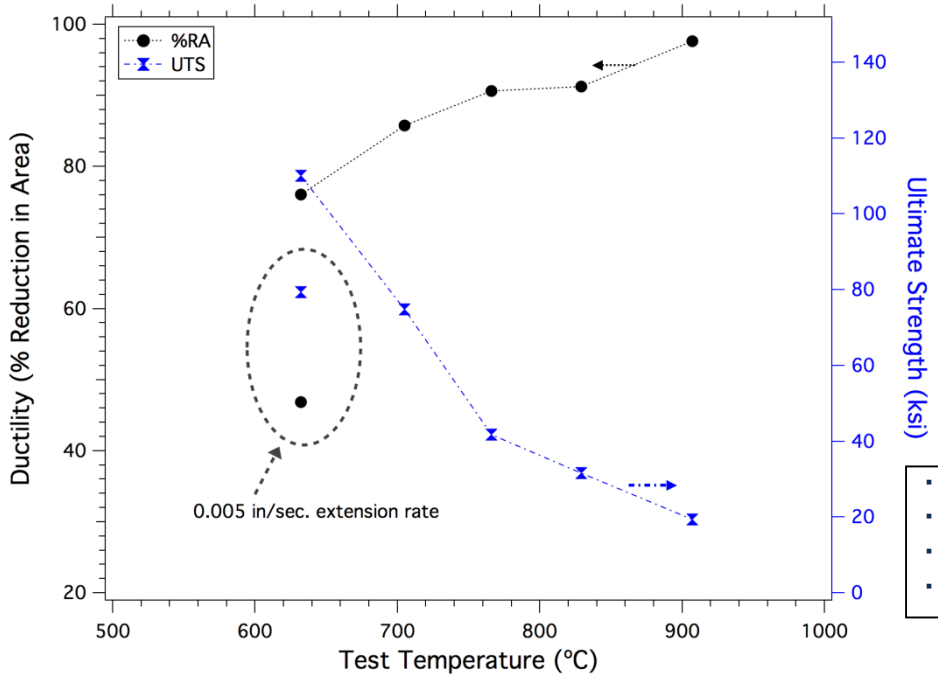
Gleeble 3500





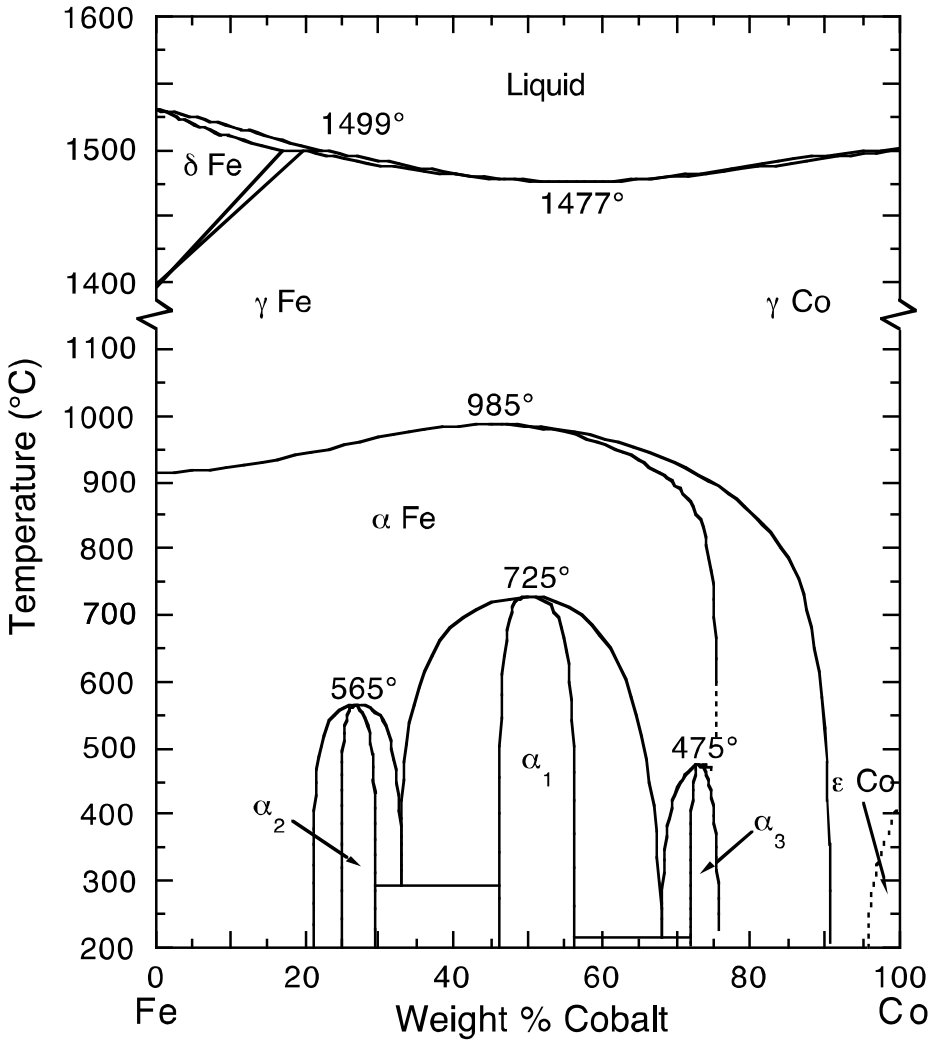
Resistively-heated sample held in tensile grips within vacuum chamber

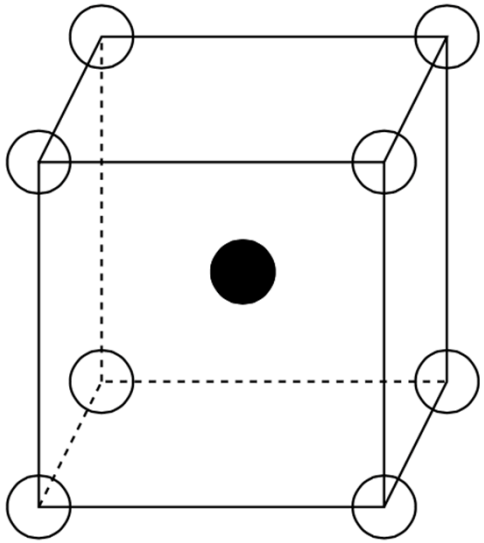
Temperature-dependent strength and ductility signature for Hiperco 50A



- Heat specimen @ 25 K/sec.
- Stabilize 30 sec. prior to extension
- Extension Rate: 0.5 in/sec.
- Atmosphere: vacuum

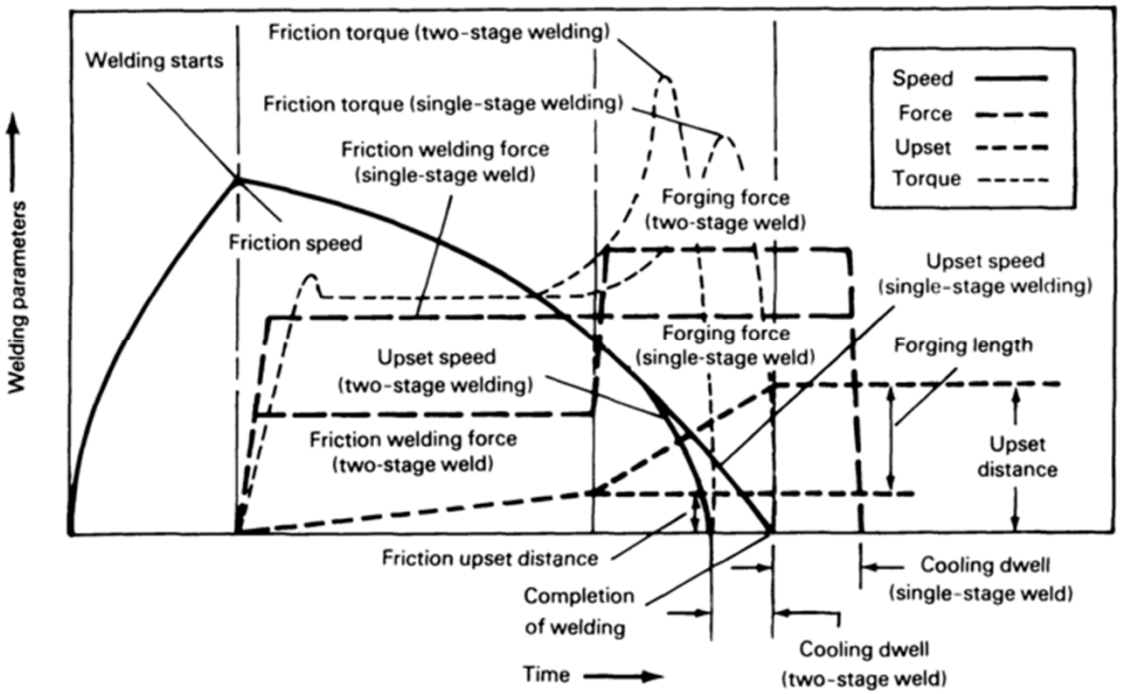
Fe-Co Binary



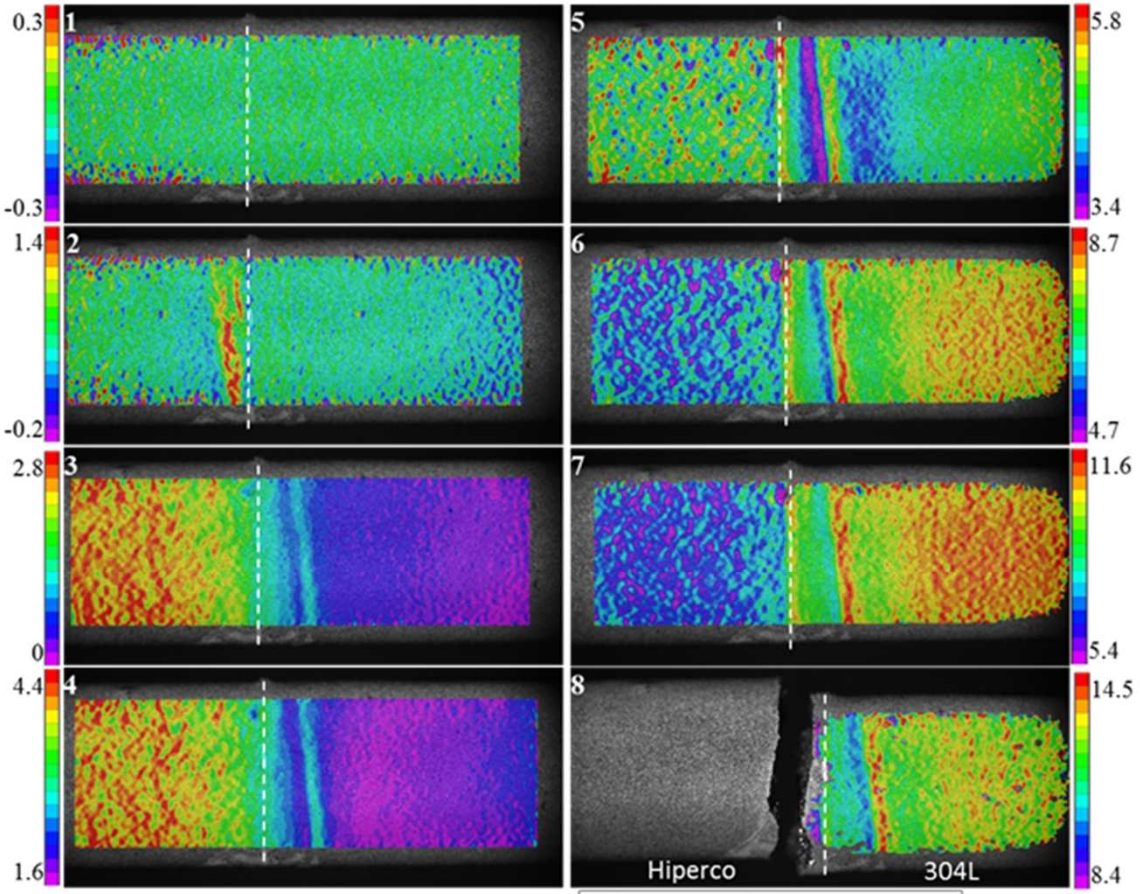


α_1 = CsCl B2

Inertia Friction Welding Process Parameters vs. Time



#1B Heat Treated – DIC data



Axial Strain ε_{xx} (%)