Progress in fundamental understanding of microstructure evolution at interfaces of metals and alloys during ultrasonic additive manufacturing

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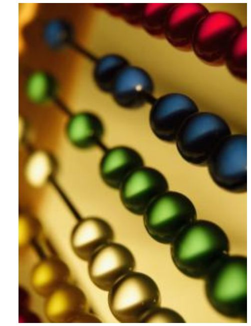
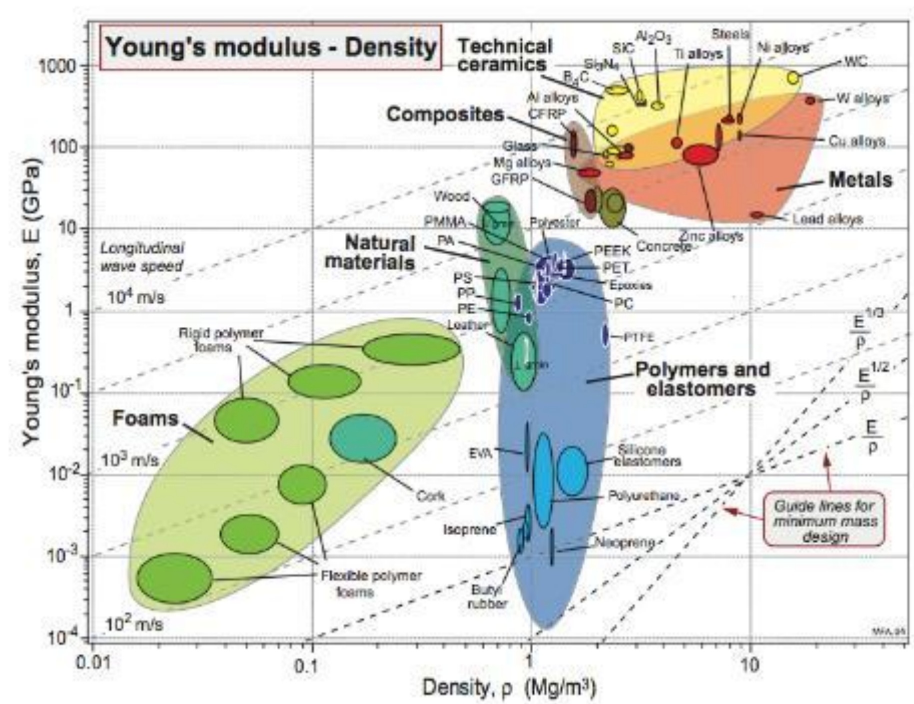
Outline (20 min Talk + 5 min Q&A)

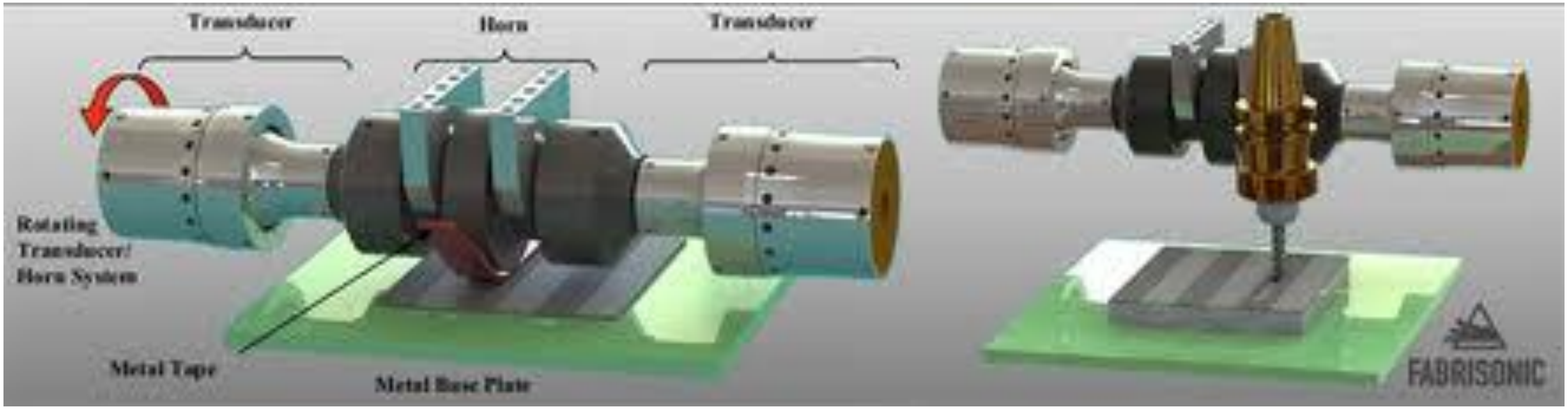


- Introduction
  - Why Additive Manufacturing?
  - What is UAM & What are the current Applications?
- Current Topic: Joining of Dissimilar Materials
- Experimental Techniques
  - Processing
  - Microstructure Characterization
  - Push-Pin Testing
- Results and Discussions
  - Al-Cu (FCC-FCC) & Fe-Ta (BCC-BCC)
- Future Directions
- Summary and Conclusions

Hybrids are now possible!



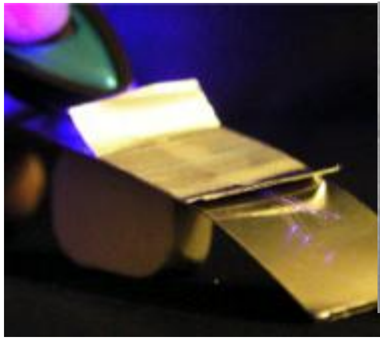
Ultrasonic Additive Manufacturing



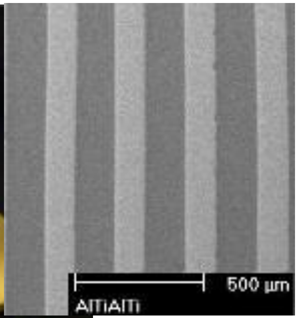
- Uses solid-state ultrasonic metal welding (UMW) to create net-shape metal parts
- Solidica® and Fabrisonic®

Potential hybrid examples:

Embedded Electronics



Embedded Fiber Optics



Armor Materials

Complex Shapes

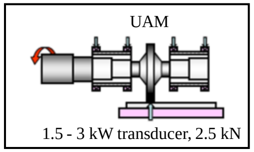
Thermal Management Parts

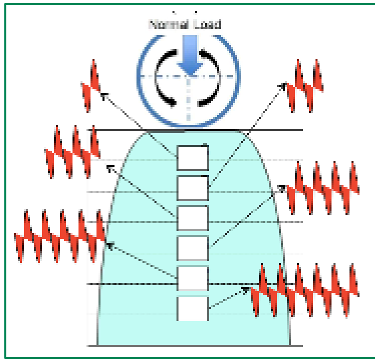
Ref: K. Johnson, Solidica
K. Graff, EWI

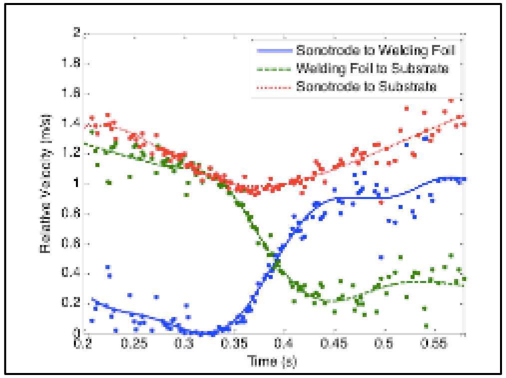
- What are the challenges and what has been done so far?

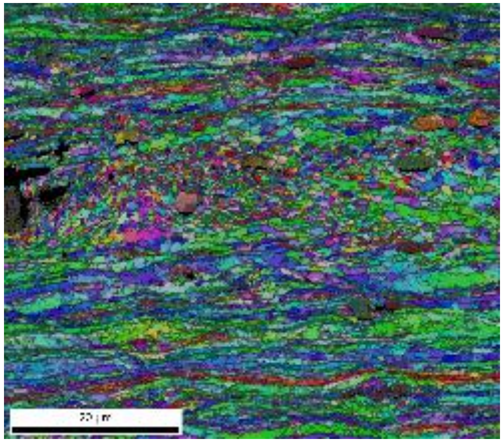
Overview of Literature:

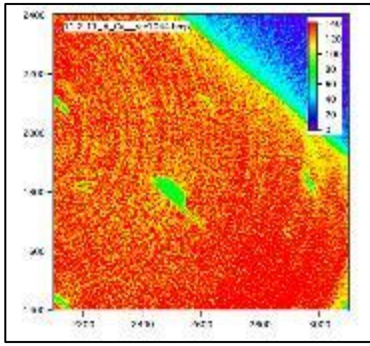
- Low Power Systems
  - 17-26 μm; 1.5 kW & 150° C (preheat)
- Process Characterization
  - Photon Doppler Velocimetry
- Microstructure Characterization
  - Optical, X-ray tomography, SEM, TEM
- Property measurement
  - Tensile, Shear & Push-Pin Testing
- Interface Joining Mechanisms
  - High Strain Rate Deformation & Adiabatic Heating
  - Dynamic Recrystallization & Boundary motion across interface

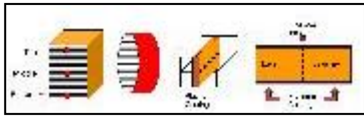




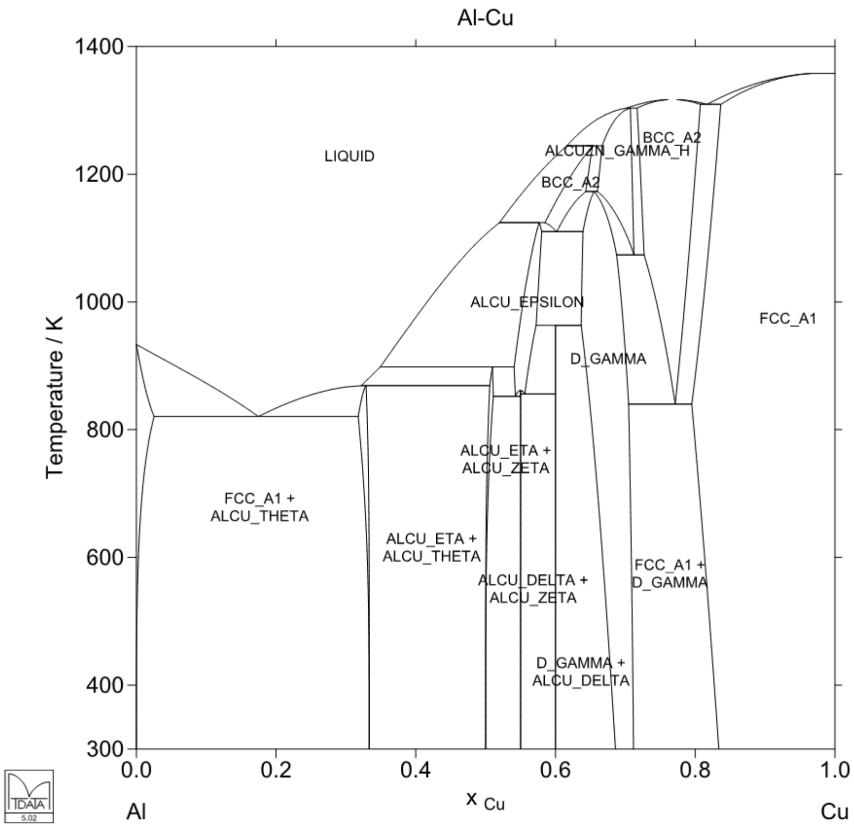


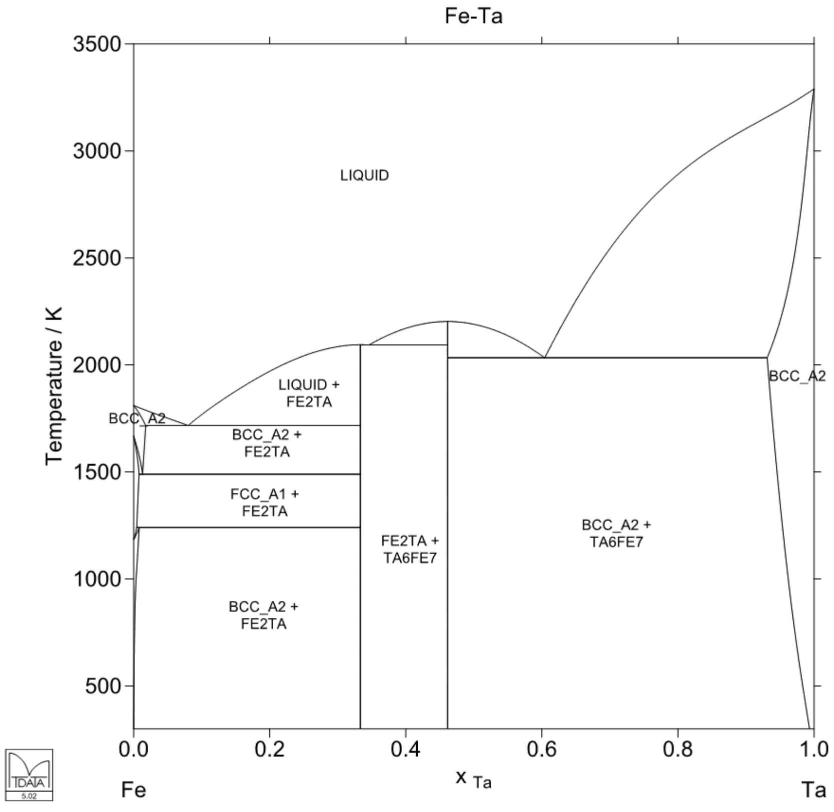






Current Focus: Joining of Dissimilar Metals: Al-Cu (FCC-FCC) & Fe-Ta (BCC-BCC) by UAM



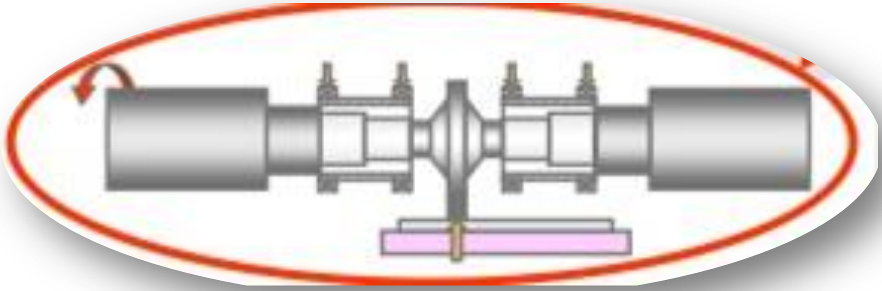


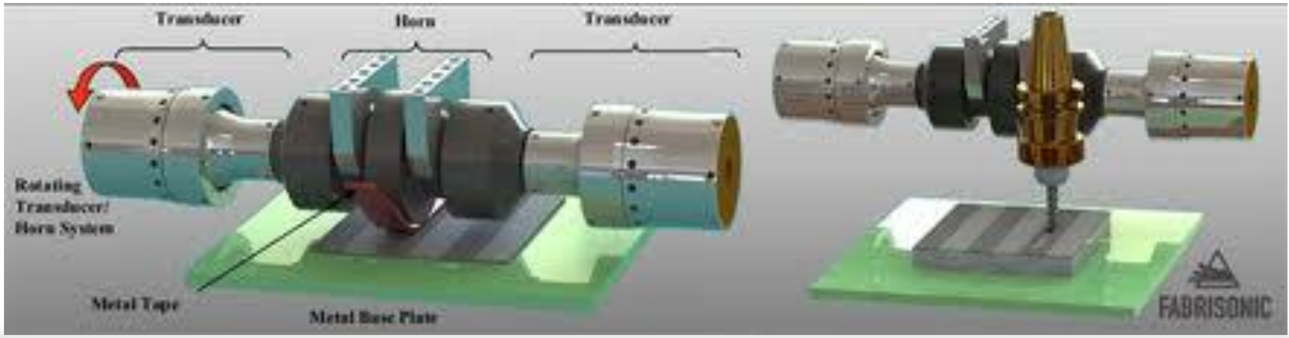
- How can we avoid these intermetallics?

Ref: MTDATA; NPL

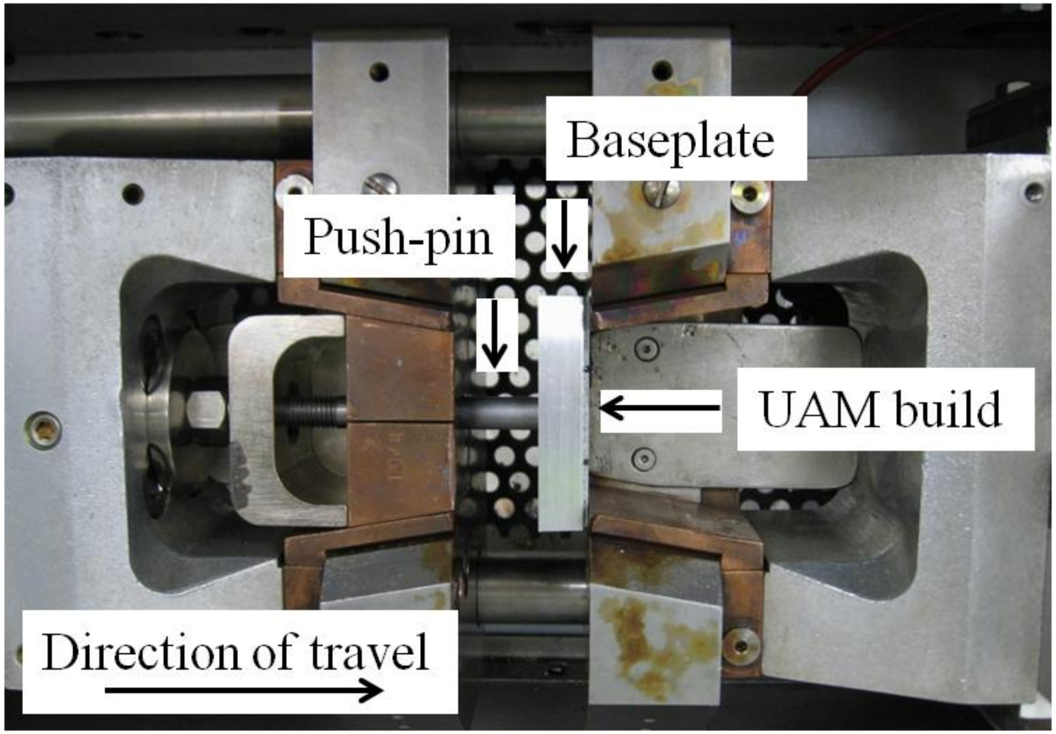
Experimental: Transition to very high power system: Increase Localized Interface Thermomechanical Deformation

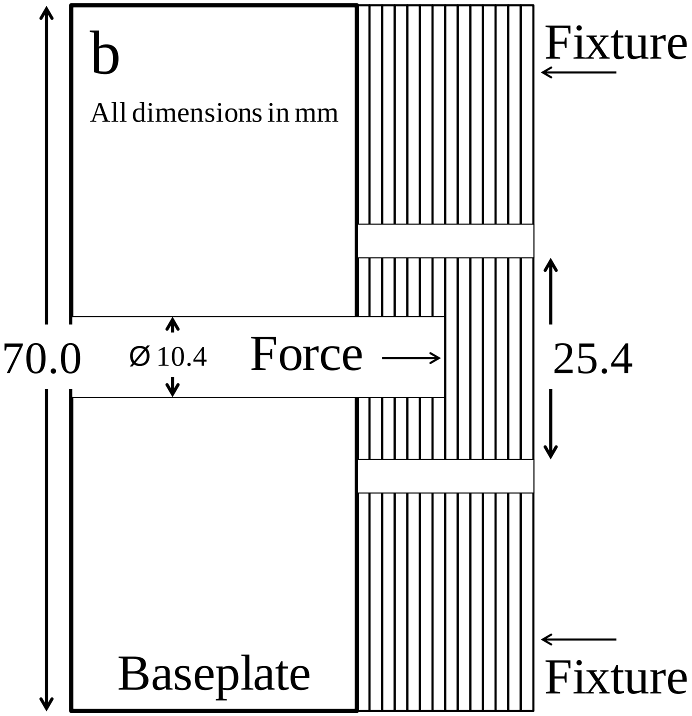
- Collaboration with EWI/Fabrisonic®
- Up to 9 kW at 100% duty cycle
- Amplitude: 52 μm (max)
- Normal Force: 15000 N (max)
- Welding Speed up to 30mm/s





Mechanical Property Evaluation of Dissimilar Builds:

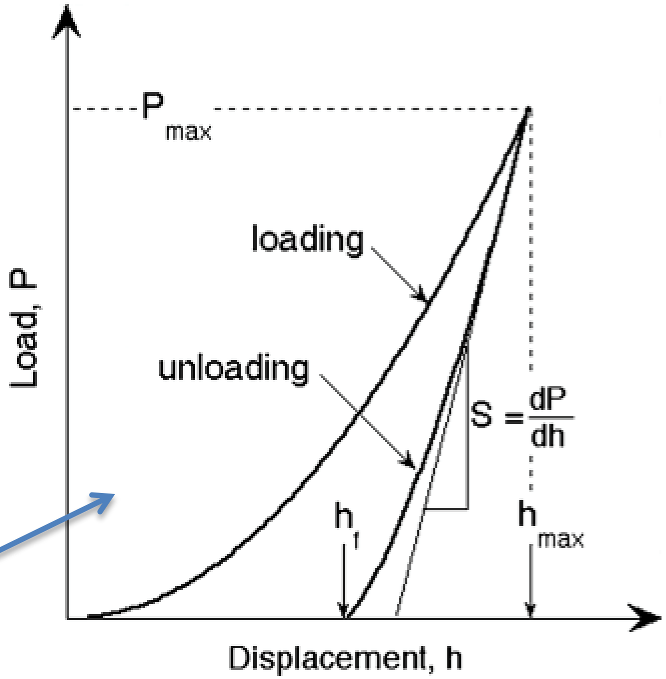


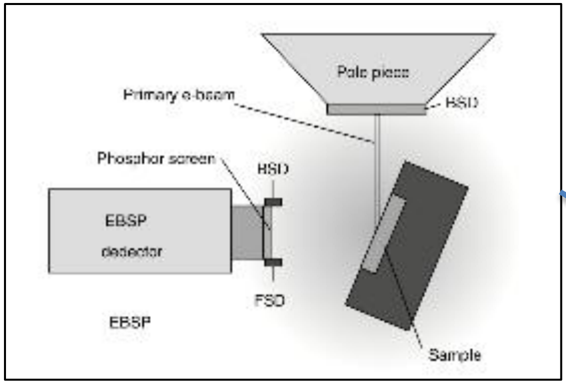


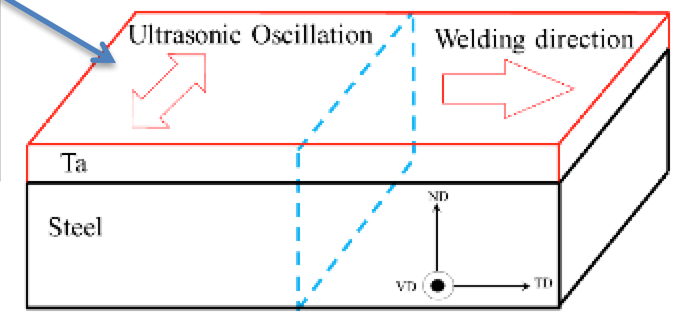
- Benefits:
  - requires few layers (14) for testing
  - special fixture is not required
  - can test specific interface

Microstructure Characterization: Optical- and Electron Microscopy & Nano-indentor

- Tools:
  - Optical Microscopy
  - Nano-Indentor
  - X-ray Diffraction
  - Energy Dispersive X-ray Analyses
  - Electron Backscattered Diffraction Imaging



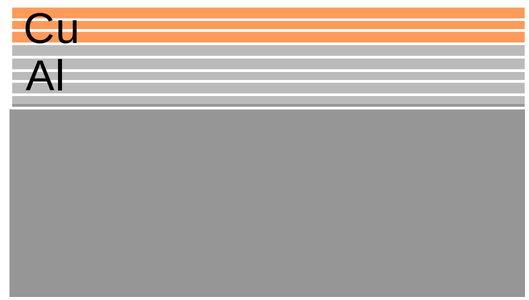




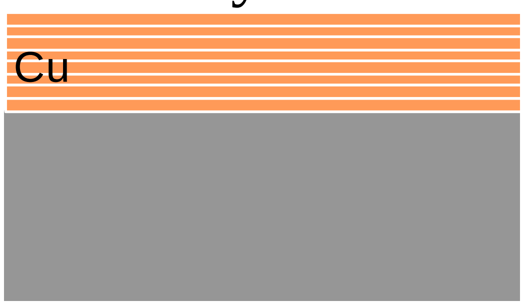
Al-Cu Experimental

- Four different build geometries were created with the same welding parameters
- Builds were heat treated at 350˚C for 10 minutes

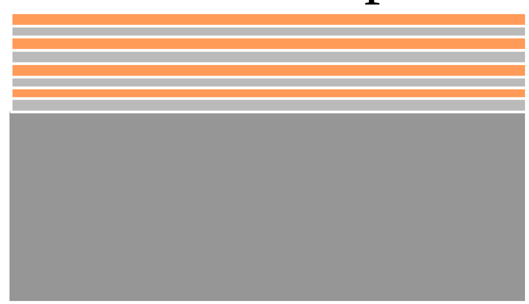
14 layers Al



Cu on top



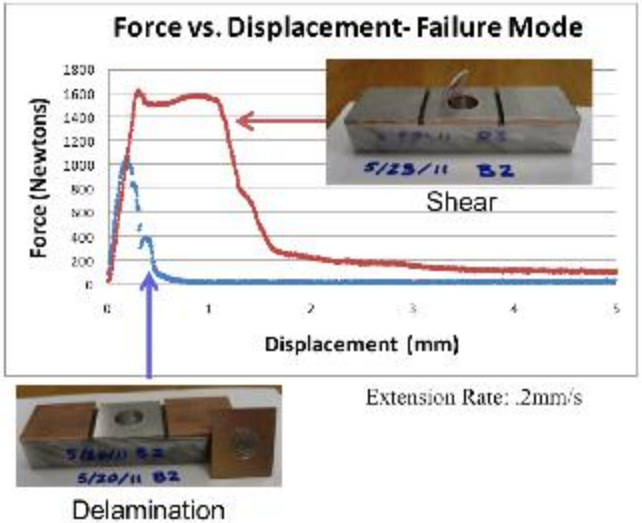
14 layers Cu



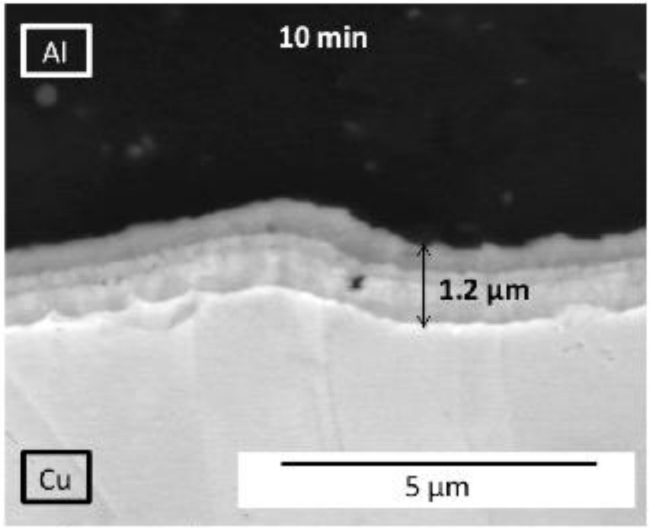
Alternating Al/Cu

<u>Process Parameters:</u>
Amplitude: 34µm
Force: 5,560 N
Travel Speed: 35.5 mm/s
Al3003 H18
Cu110

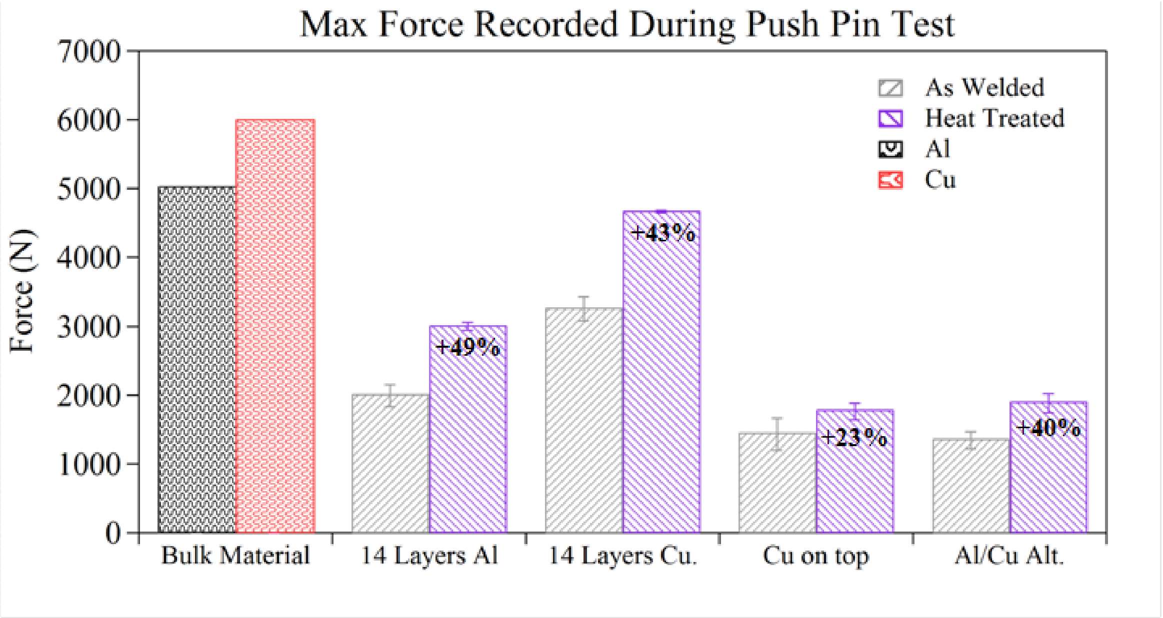
Push-pin tests show improved load bearing capacity after heat treatment



Extension Rate: .2mm/s

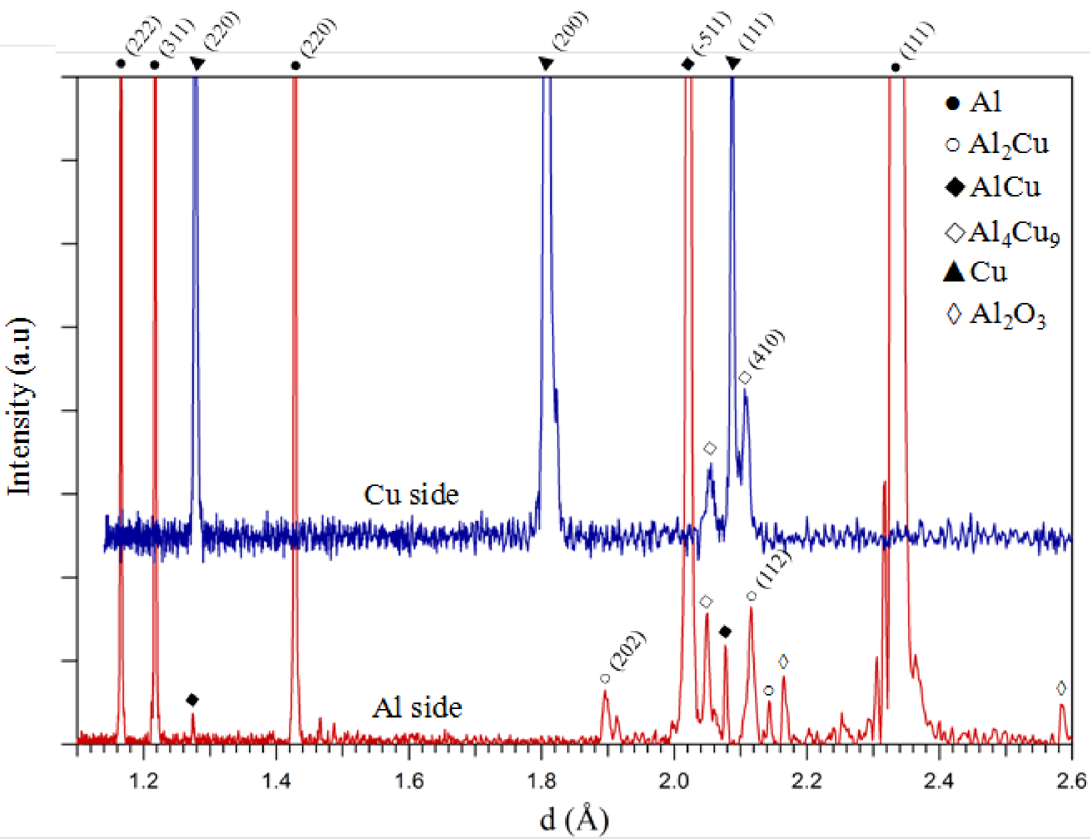


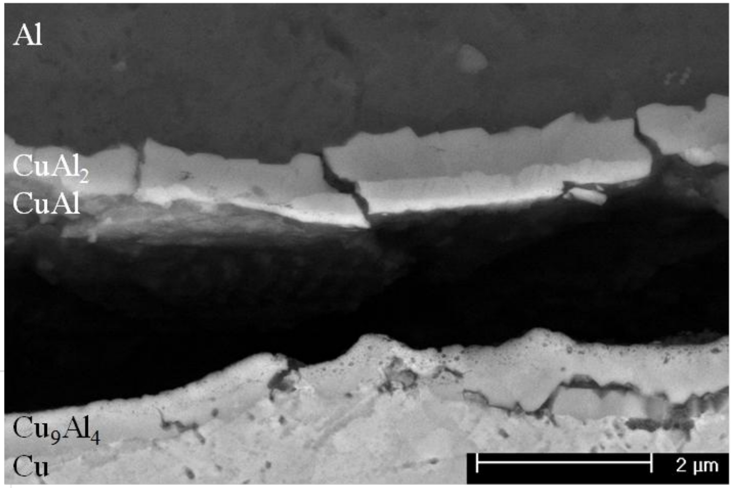
Backscatter detector

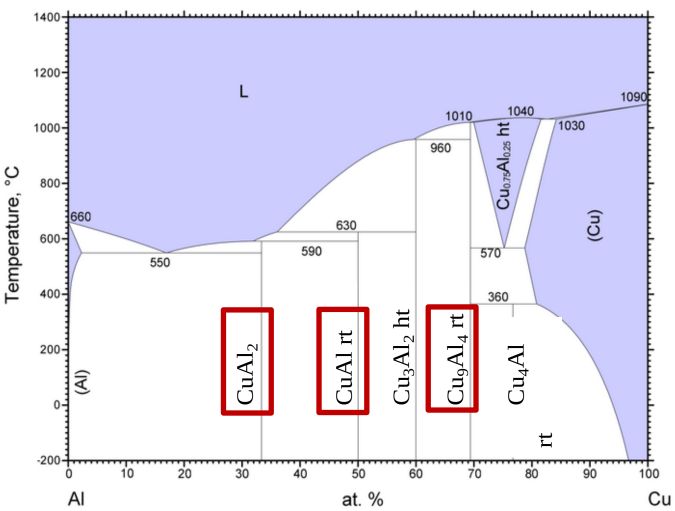


- Z-contrast show possibility of intermetallic formation:

X-ray diffraction confirmed the presence of intermetallics.



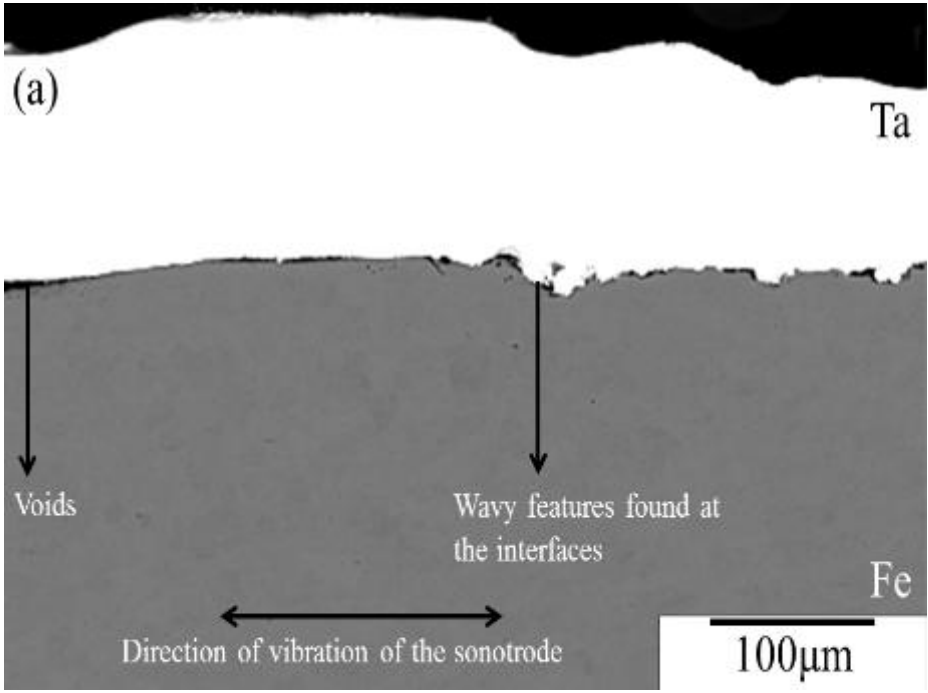


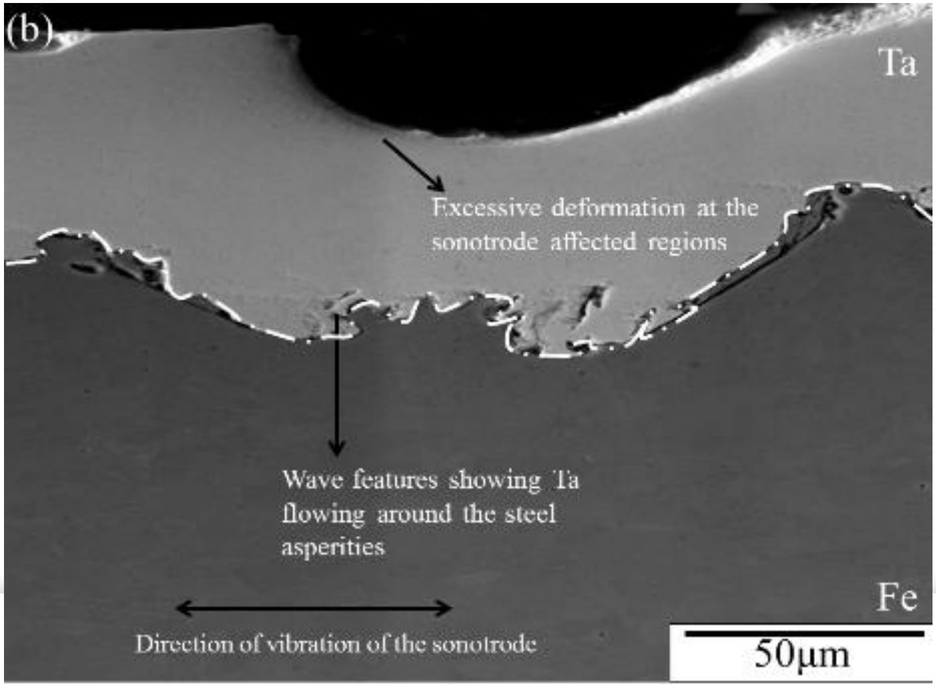


- How about the Fe-Ta interfaces?

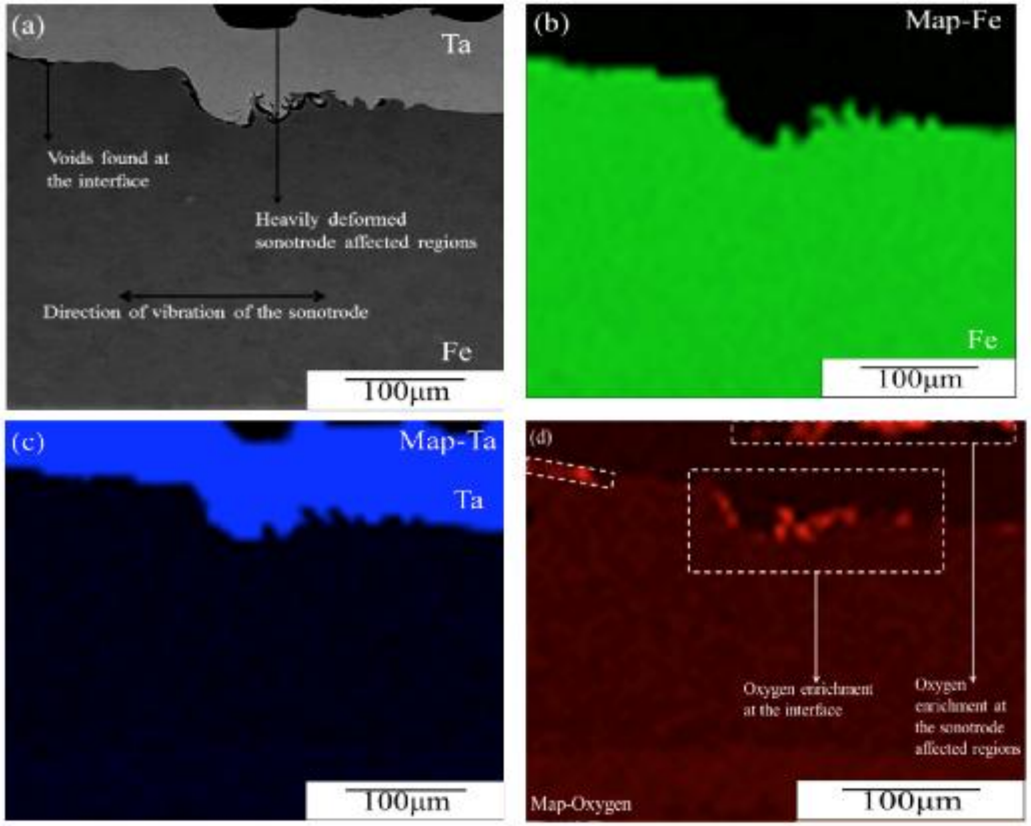
Fe-Ta Experimental & Optical Microscopy

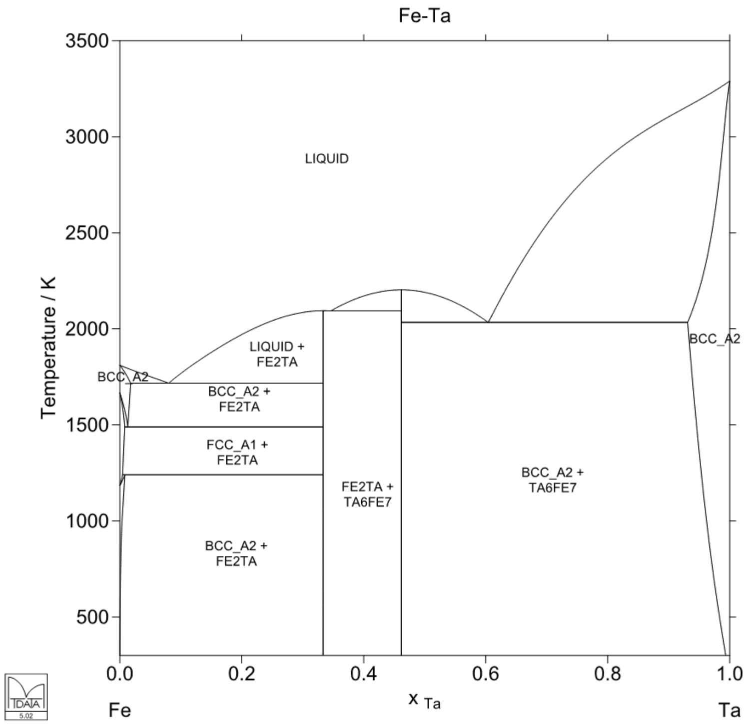
- <u>Materials</u>
  - 99.5% Pure Ta – 50 μm thick
  - Substrate: Low-Carbon Mild Steel – 2.5 mm thick
- <u>Parameters</u>
  - Amplitude: 36μm
  - Normal Force: 7000 N
  - Travel Speed: 15 mm/s
  - Single layer deposition
  - <u>No Post Heat Treatment</u>
- Complex Interface Morphology:





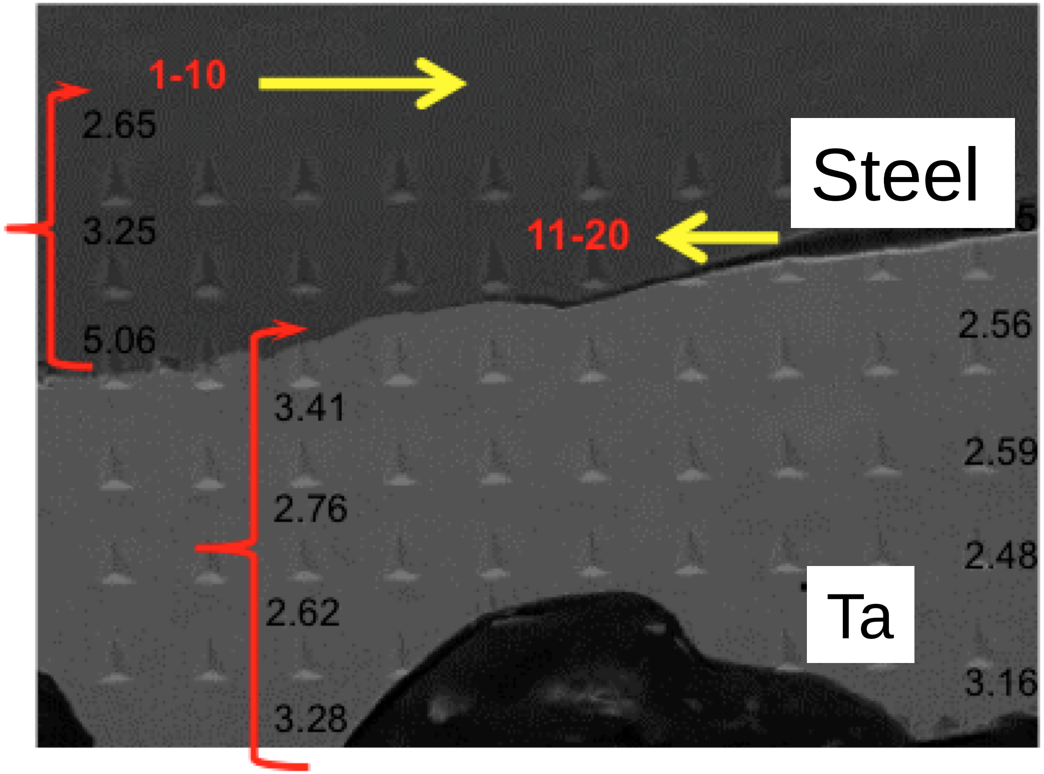
EDS Analyses fail to show any intermetallic formation:

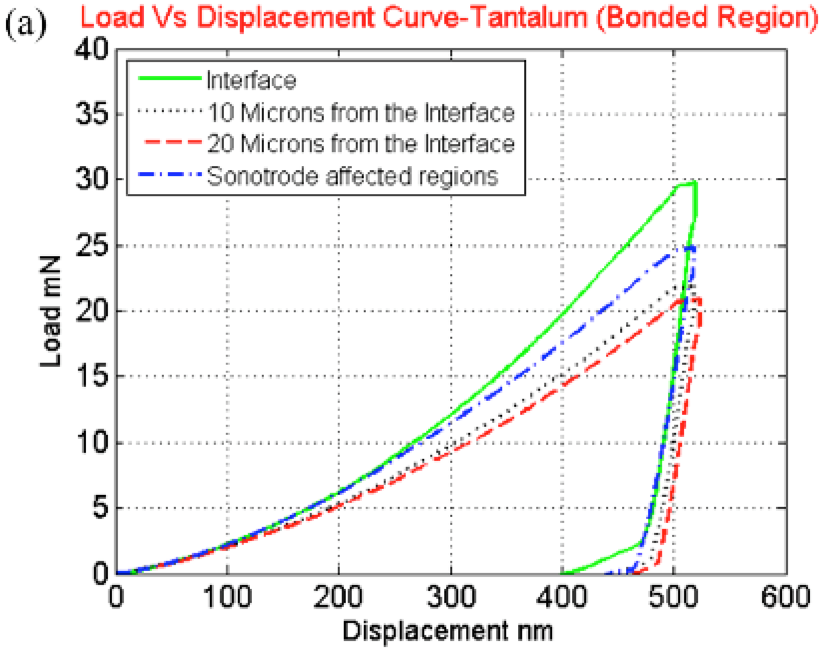


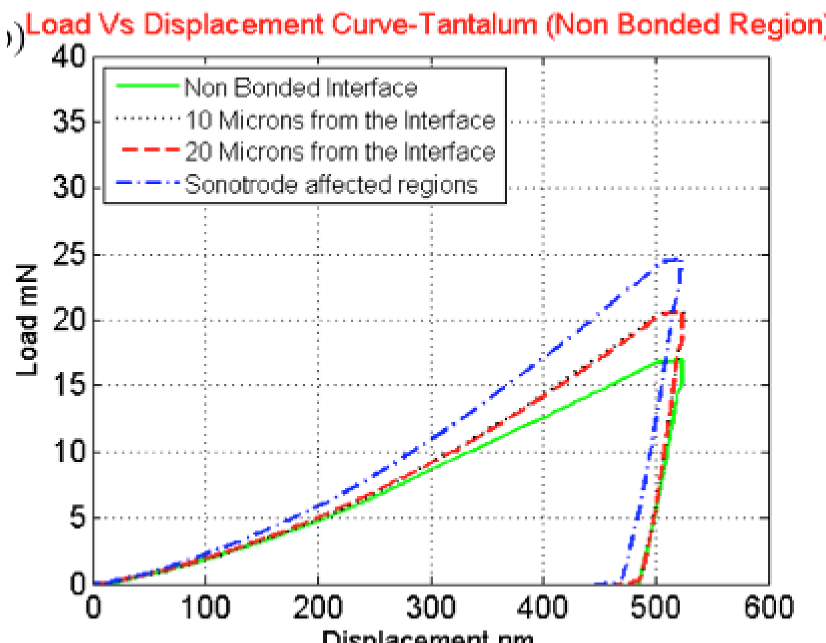


- Then, why do we get inhomogeneous bonding at interface regions?

Bonded interface regions are harder than the un-bonded interfaces





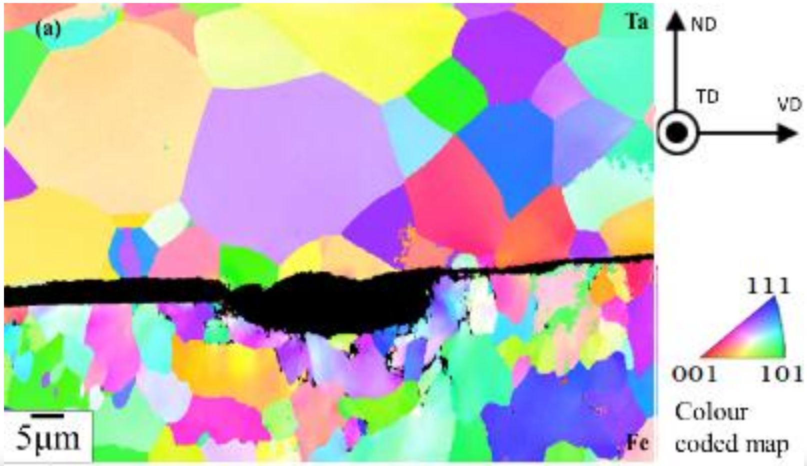


- Why do we see such behavior?

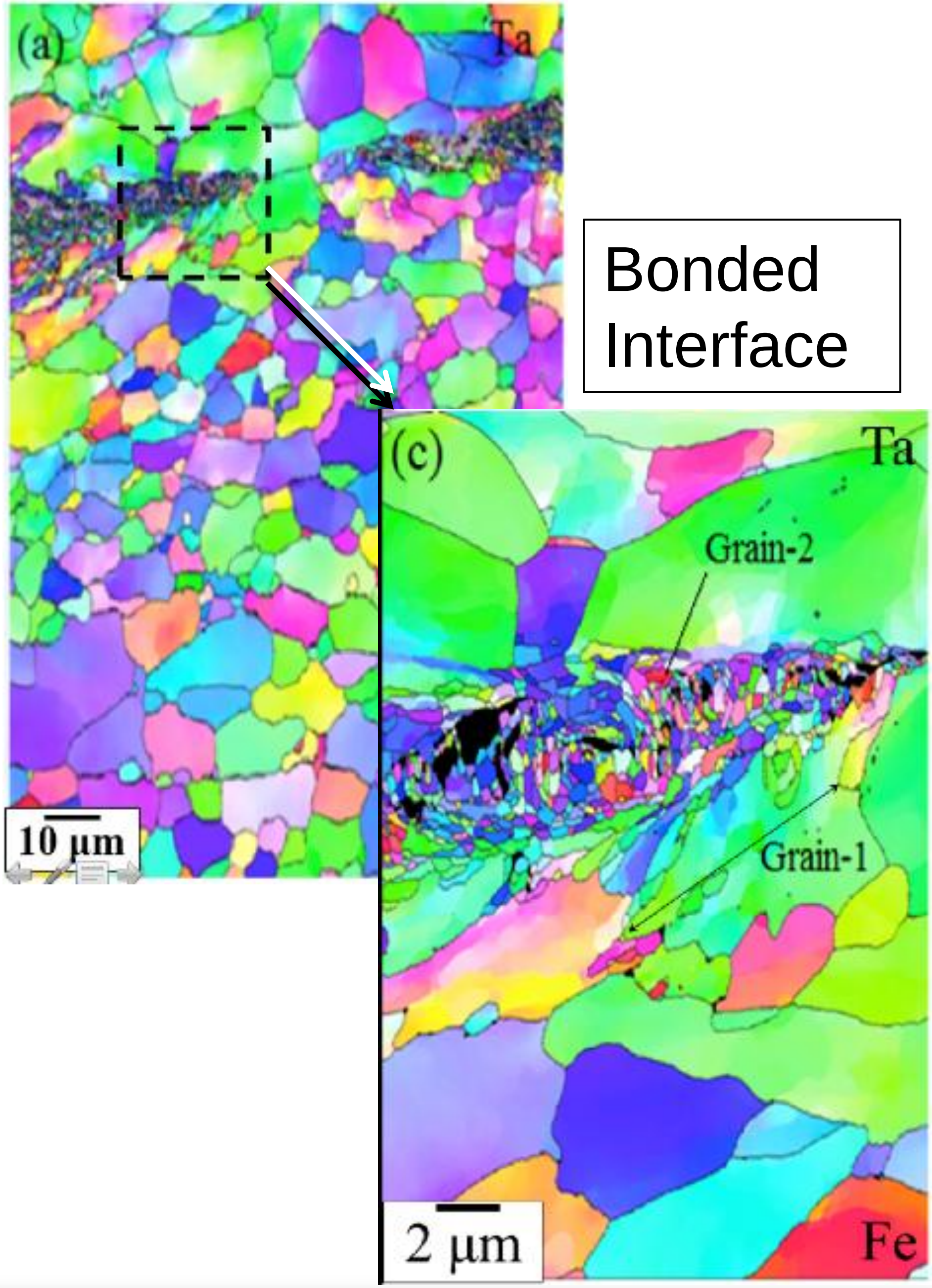
Drastic differences in crystallographic texture were observed at interfaces:

- Key: Induce uniform deformation across the interface:

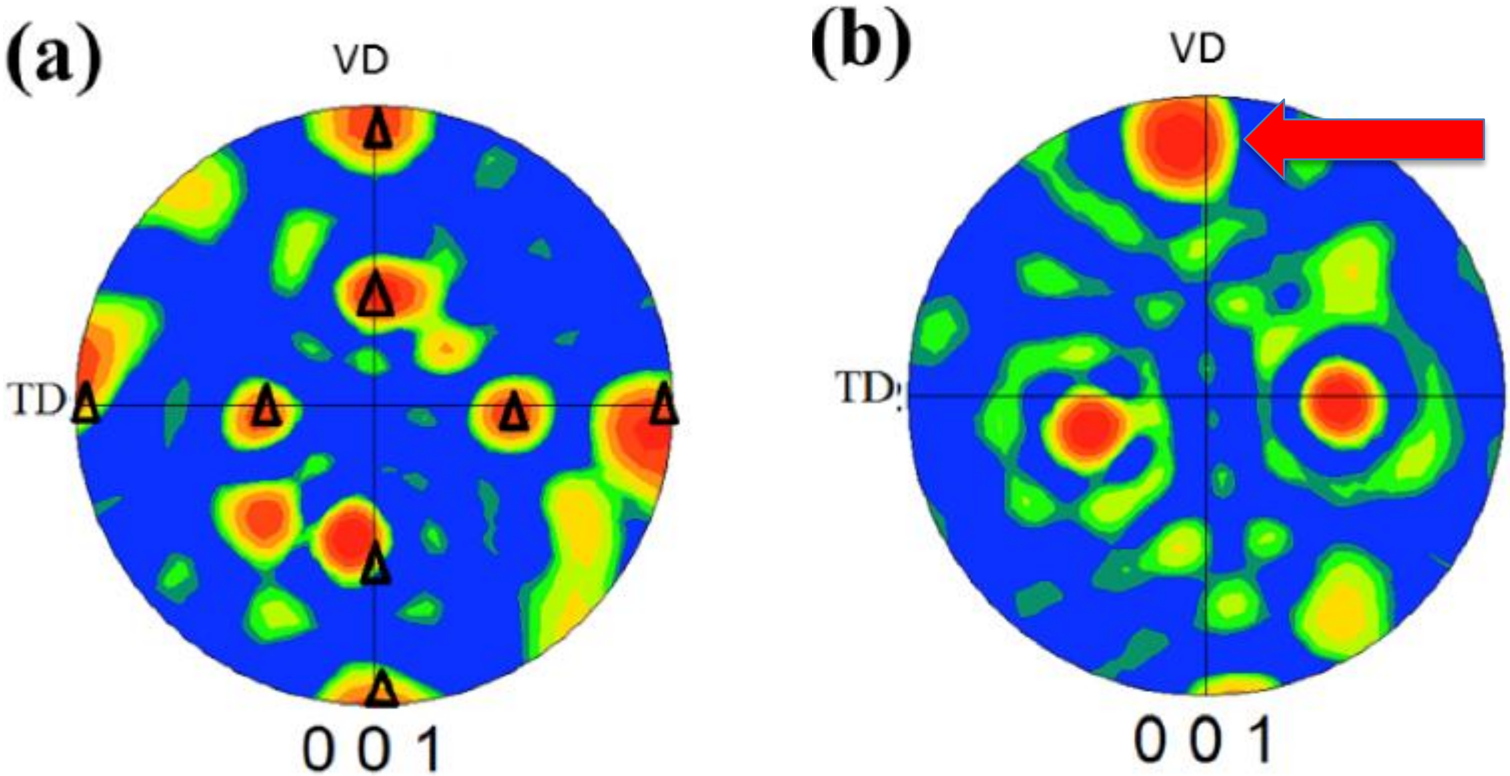
Un-bonded Interface



Bonded Interface

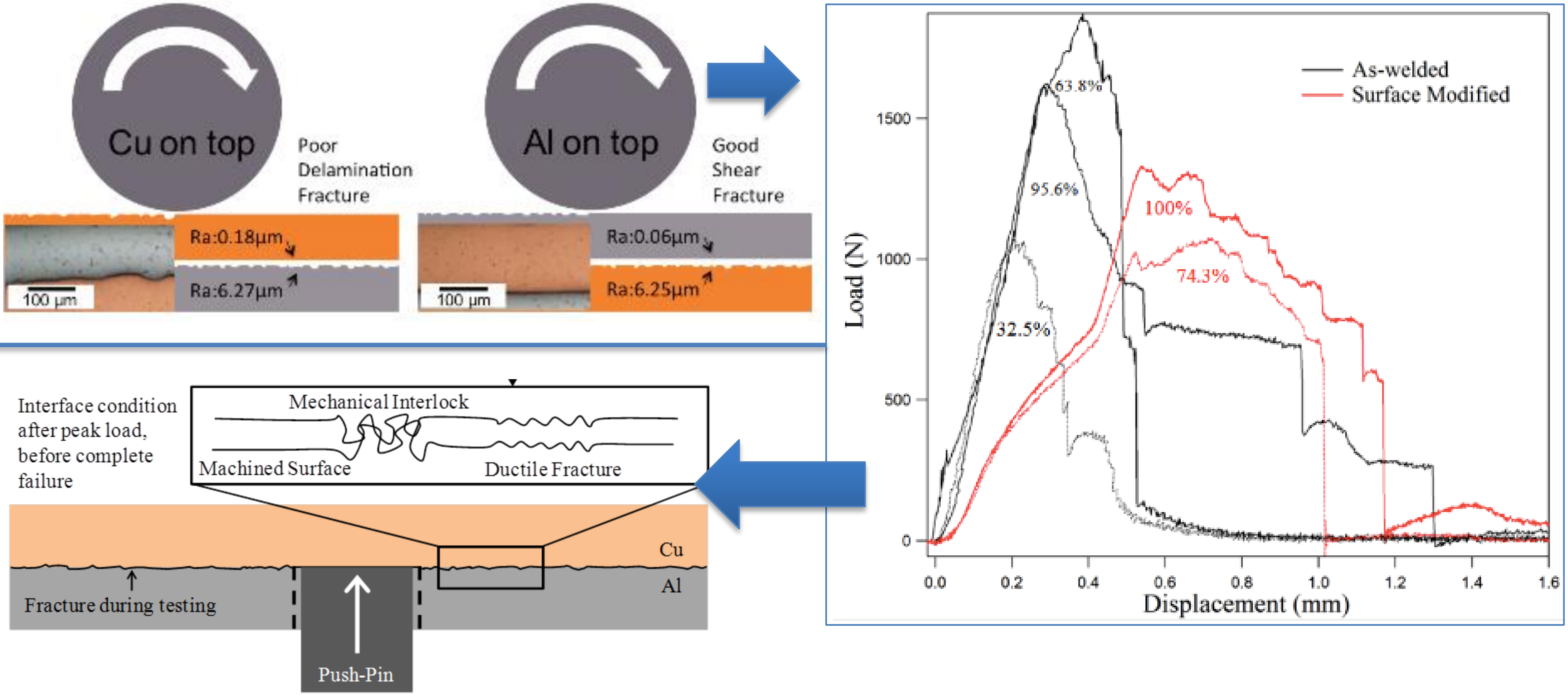


Texture Differences between (a) un-deformed regions and (b) heavily deformed regions (Goss Texture).



- Results reinforce the need for inducing uniform and excessive deformation across the interfaces.

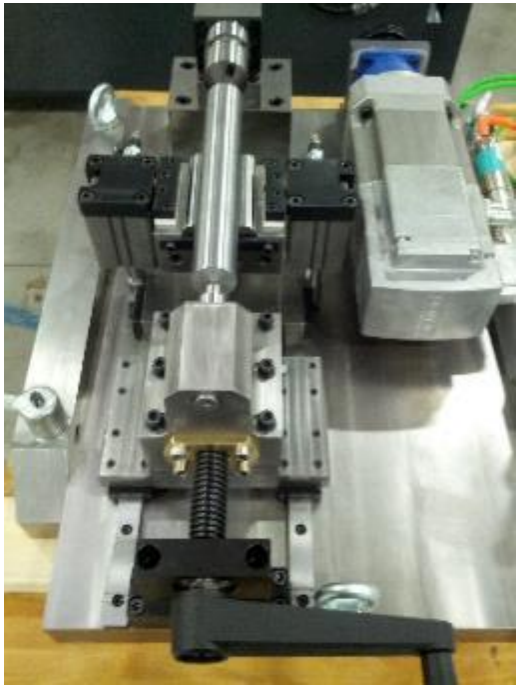
Future Directions: Engineer the surfaces to allow for effective interaction between asperities for bonding and also mechanical interlocking.



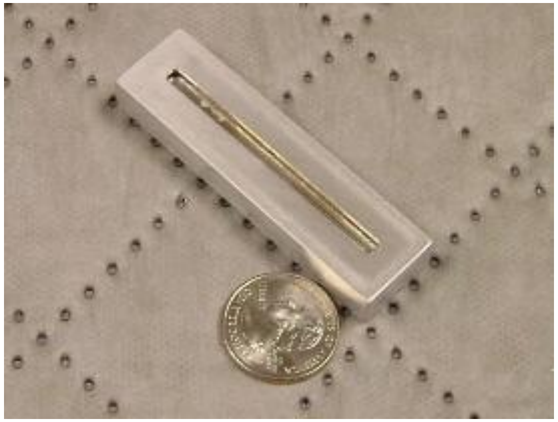
- Proof of principle exists for Al-Cu joints is completed.
- Need to extend to BCC-BCC systems

Future Directions: Ongoing research and development: Fabrisonics® and OSU:

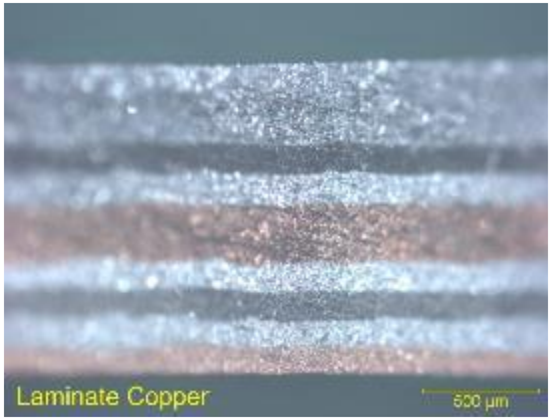
Rotary Axis

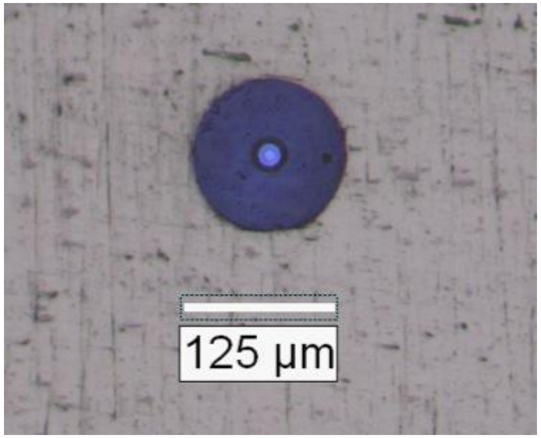


Internal Channels



Dissimilar Materials



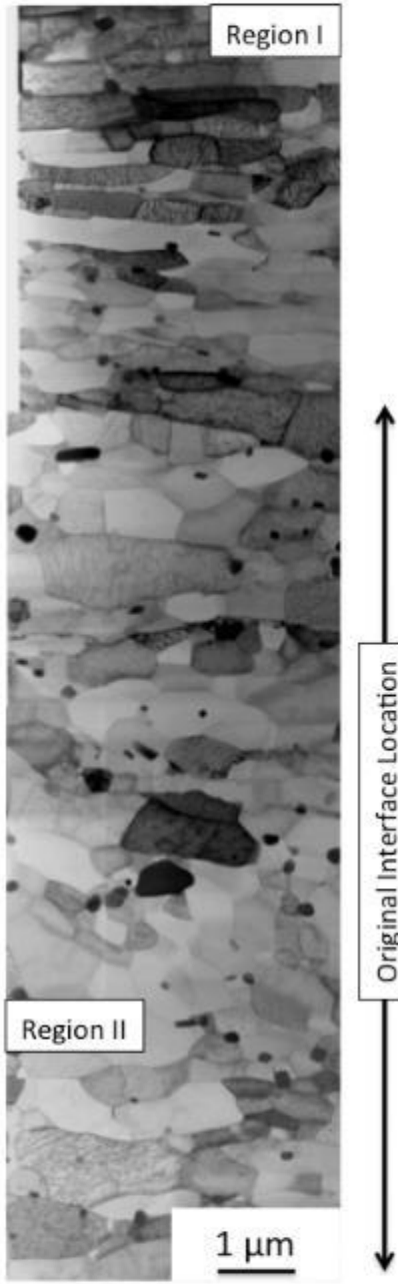


Fiber Optics

- Crucial Enablers: Fundamental understanding of physical processes at interfaces.

Summary:

- We have used comprehensive ex-situ characterization tools to interrogate the bond quality of UAM dissimilar metal (Al-Cu and Fe-Ta) builds.
- Joining mechanism relies on excessive high strain rate plastic deformation, adiabatic heating, and recrystallization/recovery of the deformed grains.
- We have also developed methodologies to improve bond quality by process optimization, pre- and post-processing of foils and builds.
- There are many unanswered questions with reference to complex deformation conditions at the interfaces and oxide dissolution.



Questions and Comments

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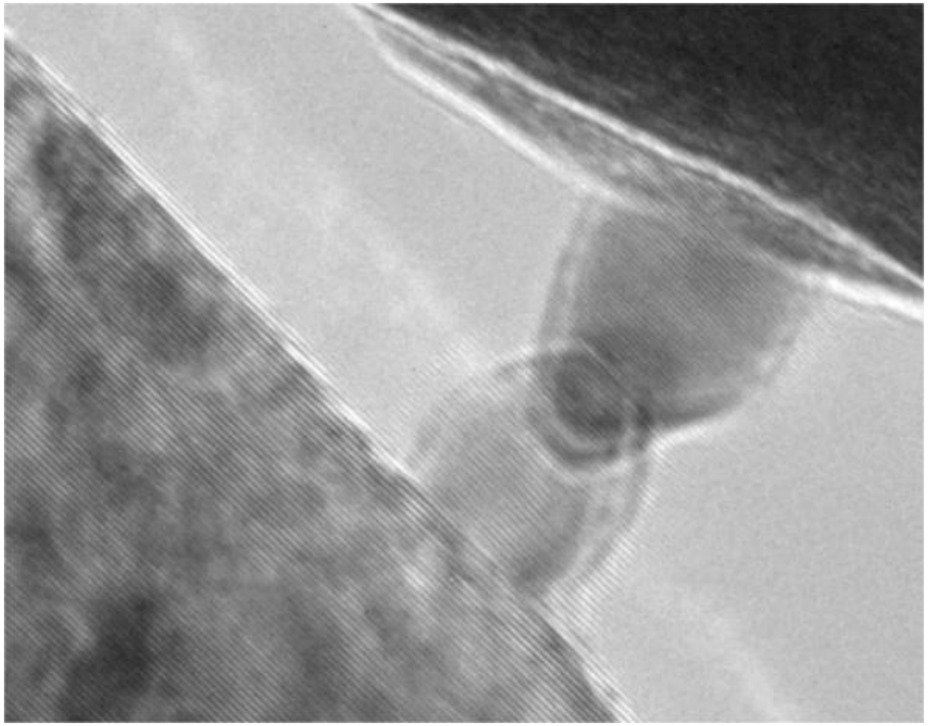
Barriers to solid-state joining

- Atomically clean metal to metal joining should be spontaneous!
- Contact is hindered by three surface barriers:
  - Asperities
  - Oxides
  - Surface contamination
- How do we get rid of these barriers?



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Cold welding of ultrathin gold nanowires

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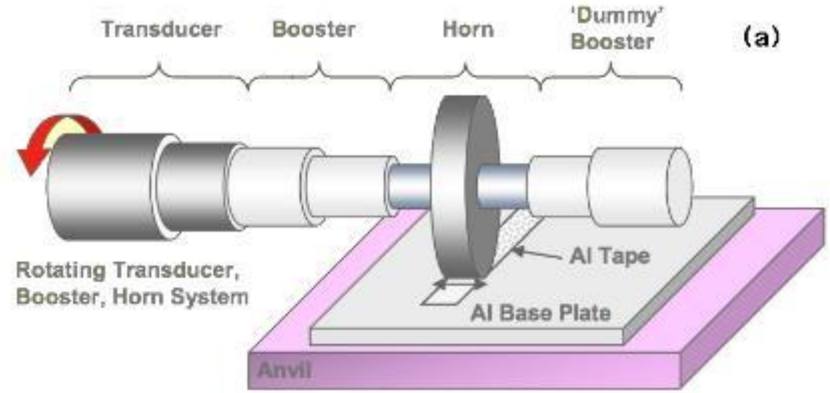
Low-Power Systems



- **Materials:**
  - **6061-H18 & 3003-H18**
- **1.5 kW Solidica formation™**
- **UAM Process Parameters**
  - **Substrate Temperature:**
    - **300° F (~150° C);**
  - **Frequency: 20 kHz**
  - **Tack Pass:**
    - **12 µm (ampl), 200-350 N**
    - **60-140 ipm (25-59 mm/s)**
  - **Weld Pass:**
    - **17-26 µm (ampl), 1150-1800 N;**
    - **100 ipm (42 mm/s) (for 3003 only)**
    - **25 - 35 ipm (20.6 to 14.8 mm/s) – 6061**