Recent Developments in Welding Alloy 740H

John deBarbadillo, Ronald Gollihue & Brian Baker

Special Metals

Presentation Outline

- Different not too Difficult
- Physical and Chemical Metallurgy of 740H Weldments
- Evolving AUSC Code Case for 740H
- Boiler Tube and Pipe Welding
- Seam Welded Tube and Pipe
- Continuing Investigations

Background

- Thermie (1998)
  - 740, Boiler tube resistant to fireside corrosion
- DOE AUSC (2002)
  - 740H, Steam transfer pipe
  - Heavy section welding
  - ASME Code Case 2702, 2011
- sCO_2 Demonstrations (2012)
  - Net Power
  - SwRI Sunshot/STEP
- Gen 3 CSP (2017)
  - Seam welded tube and pipe
  - Heat Exchangers
- University Research (2010)
  - Stress relaxation cracking
  - Microstructure stability

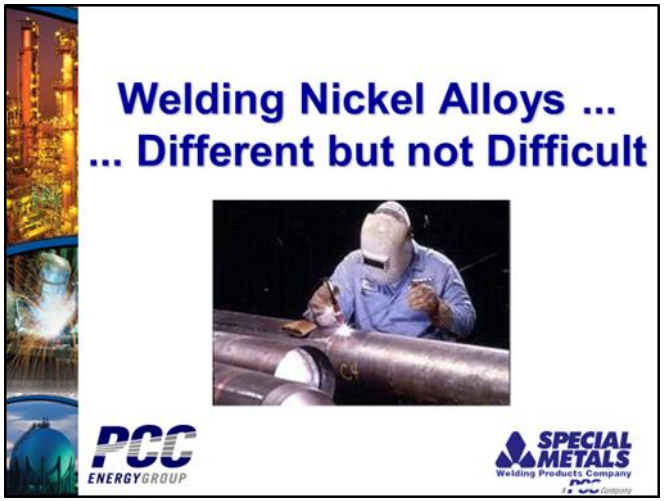
Evolving Applications and Technical Requirements

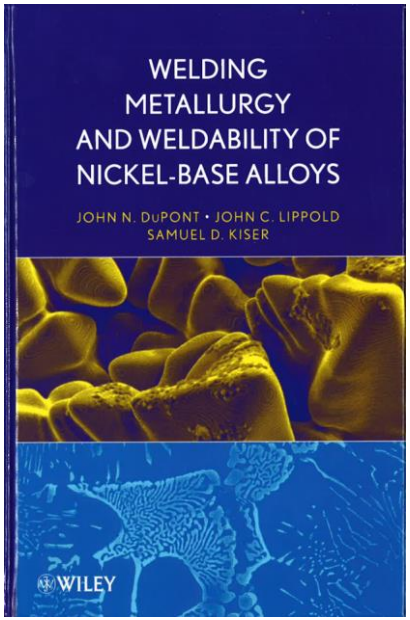
740H Welding Basics

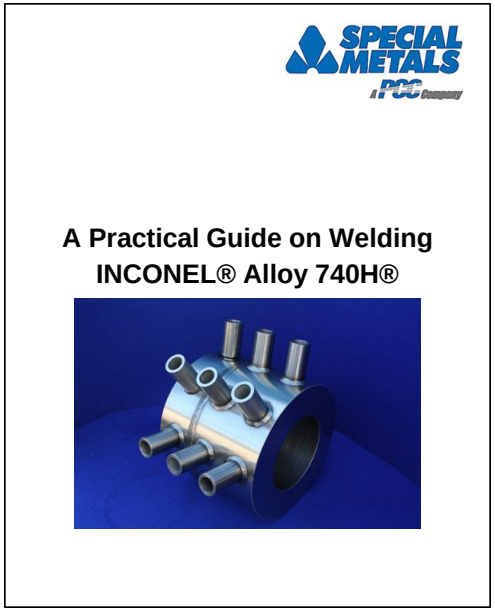
Different but not too difficult

Nickel-base Superalloy Welding

- **Physical Behavior**
  - **Composition**
  - **Age Hardening**
  - **Solidification**





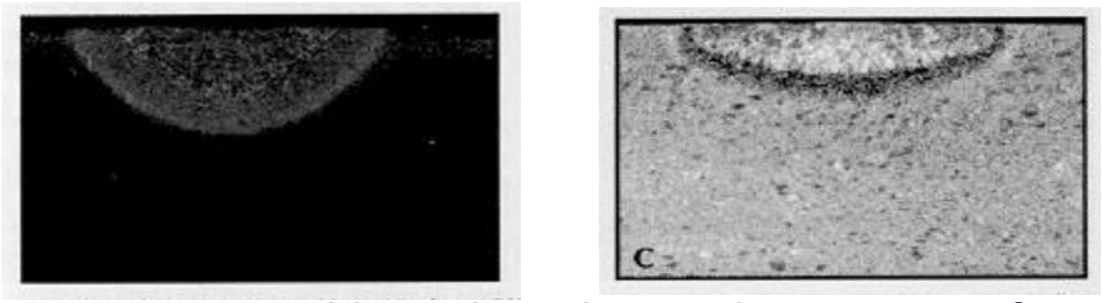


Nickel-base Alloy

- **Cleanliness**
  - Ni-Cr oxides are solid – can be trapped
  - Cannot be removed by wire brushing
  - Metal surfaces must be clean
  - Embrittling elements – S, P, Pb Zn
- **Weld penetration**
  - Less penetration than steel
  - Plan for more passes
- **Weld metal fluidity**
  - Less fluid than steel
  - Welder intervention

Oxide build-p on a 740H weld bead

Example of sulfur embrittlement

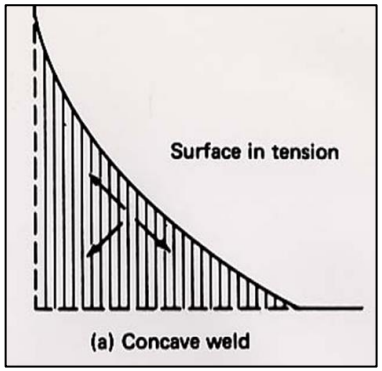


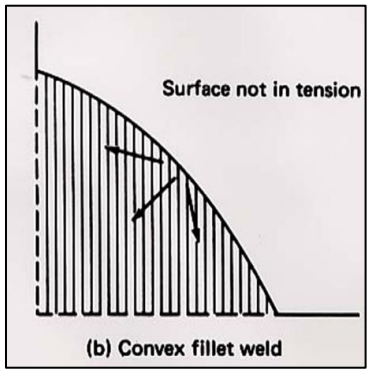
Welds made with same heat input. Left carbon steel, right alloy 600

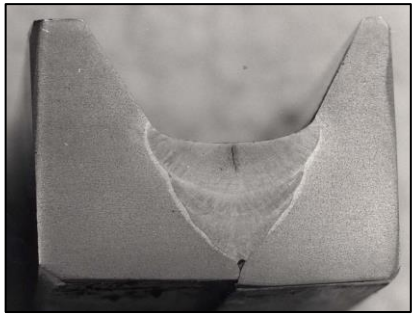
Nickel-Base Alloy

- **Bead shape requirements**
  - **Bead must be convex**
  - **Crater cracking**
  - **Many starts and stops in thick section weld**
  - **Most common problem for 740H**

Excessive reinforcement







Crack in concave bead

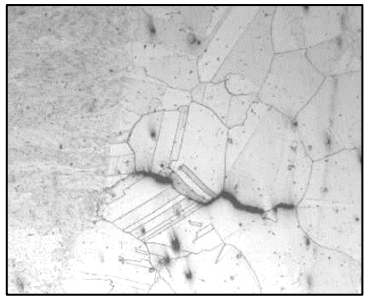
Crater crack

Chemistry

- 740H contains 1.5% Al, Ti, Nb
  - Much more reactive than Ni, Cr, Mo
  - Contributes to slag, porosity and oxide inclusions
- Reaction with atmosphere
  - Inert gas shielding is essential
  - System purge for field closure weld
- Reaction with slag
  - 740H has significant loss of Al in SAW and SMAW
  - Greatly reduced creep strength
  - 263 with 0.45% Al is more stable
  - Available as coated electrode for SMAW
- Liquation cracking
  - Encountered in thick section welds
  - 740 to 740H by lowering B, Si, Nb in base metal composition

Sugaring from inadequate gas purge

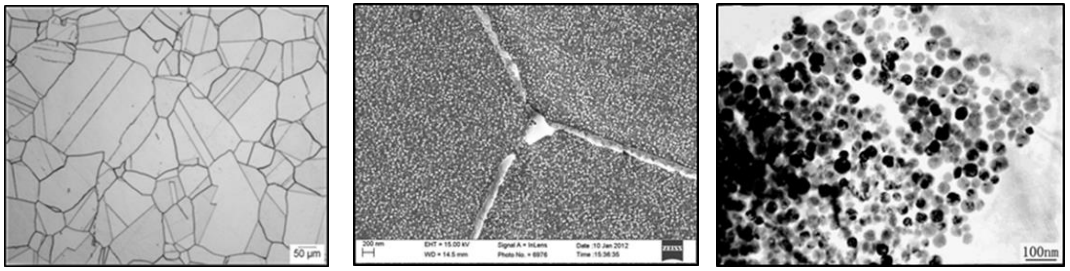
Oxide inclusions trapped in a weld deposit



HAZ liquation crack in 740

Age Hardening

- γ′ forms rapidly in 740H
  - Precipitates not visible by optical microscopy
  - Auto aging cannot be avoided in section > 1”
  - Each weld pass will partially age layer below
- Stress relief cracking
  - A form of strain-age cracking
  - Welding stress + prestrain + precipitation X stress relaxation
  - Joint design, weld notches
  - Heating rate for PWHT
- Stress relaxation cracking
  - Cracking in service after 1000s of hours
  - Undefined for PWHT 740H



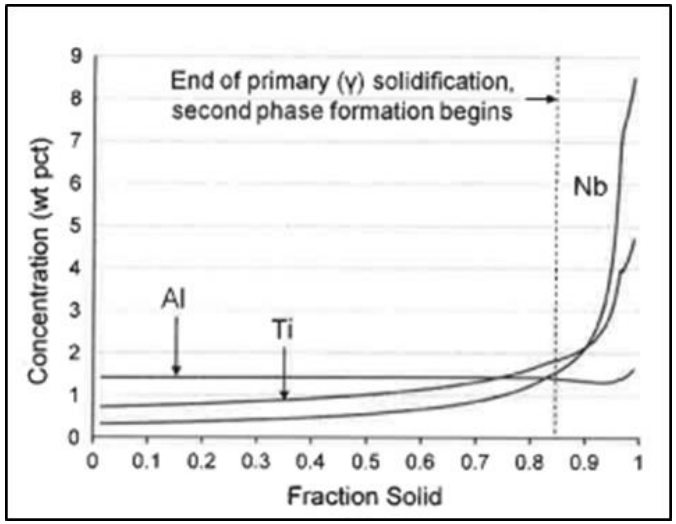
Microstructure of 740H, Optical, SEM, TEM. Images by X. Xie

Examples of stress relief cracks initiated at weld notches

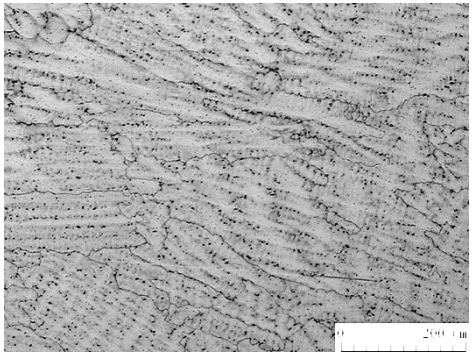
Stress relief crack at toe of weld

Solidification

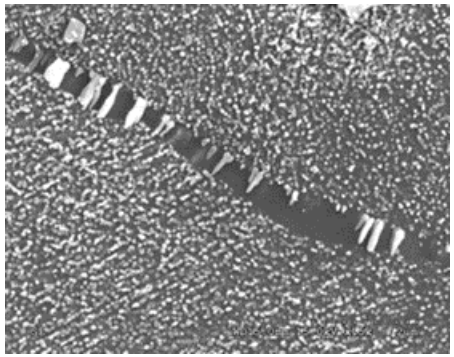
- **Major element partitioning**
  - **γ′ is not uniformly distributed**
  - **Precipitate-free zones**
  - **Carbides resist coarsening and recrystallization**
  - **Enhanced creep rate**
- **Shrinkage/crater cracking**
- **Convex bead**
- **Heat input, preheat**



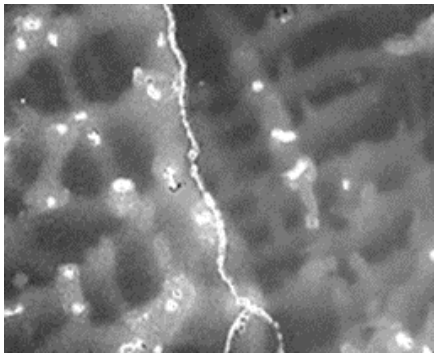
Calculated inderdendritic segregation in 740H (Bechetti)



Carbides highlighting dendrite structure (Tung)



Discontinuous γ′ growth and PFZ (Bechetti)



Non-uniform γ′ (Tung)

ASME 2702 Welding Requirements

2702 Rev 0

1. Weld procedure qualification
2. Seamless tube
3. Material in annealed and aged condition
4. Welding solid bare wire
5. GTAW or GMAW only
6. 740H to 740H – matching filler only
7. Procedure per Section IX except: Guided bend test can use 4T min radius
8. PWHT mandatory
9. PWHT matches approved aging cycle
10. No local solution annealing is permitted
11. WSRF of 0.70 for use above 600°C

2702 Rev 6

1. Weld procedure qualification
2. Seamless and welded tube
3. Material annealed or aged
4. Welding solid bare wire*
5. GTAW or GMAW*
6. 740H to 740H - matching filler only*
7. Procedure per Section IX P46 except: Guided bend test can use 4T min radius
8. PWHT mandatory
9. PWHT matches approved aging cycle§
10. No local solution annealing is permitted
11. WSRF of 0.70 for use above 600°C‡

Future ASME Code Enhancements

* 263 SMAW approval will be Rev 7

§ Solution annealed weld creep strength data being generated

‡ Re-calculation of minimum stress allowables initiated
Section VIII submission in ballot

Field Welding Experience

- **Welders and training**
  - **Communication**
  - **Qualification**
- **Technique**
  - **Thermal management**
  - **Cleaning**
  - **Bead shape and reinforcement**
  - **Weld termination**
- **Design**
  - **Joint geometry**
  - **Cover gas**
  - **Post weld heat treatment**
  - **Inspection**
- **Equipment**

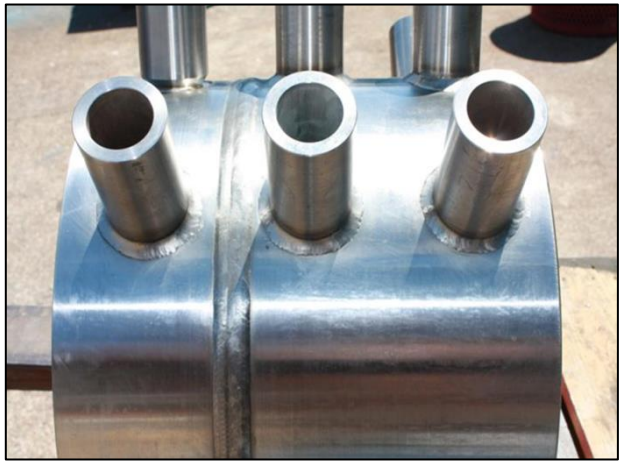
Bent and welded spool, Shaw

Tee welded in place at plant site, Net Power

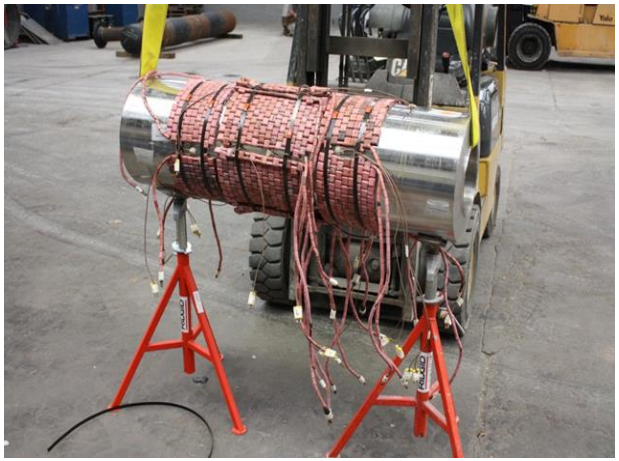
Heavy Section Welding

- Initial AUSC demonstrations on 3” T plate and 14.9” OD x 3.5” W pipe at Babcock & Wilcox
- Current demonstration on 22” OD x 3.7” W pipe by GE/Arc Applications
- Narrow-groove hot-wire GTAW
- Heat input, bead shape, inter-pass grinding

22” OD x 3.7” W pipe extruded at Wyman-Gordon



Header mockup

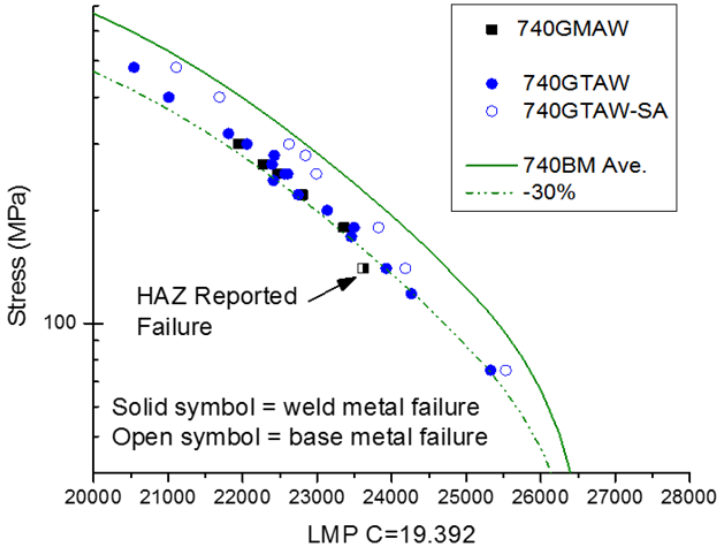


PWHT with ceramic pad, Huntington Testing

3” T 740H weld, 1° bevel

Solution Annealing

- **Welding with base metal in solution annealed condition**
  - **No special problems**
  - **Resolves some fabrication issues**
- **Solution annealing or homogenizing welds**
  - **Recrystallization**
  - **Dendritic segregation**
  - **Carbide stability – Bechetti**
  - **Significantly improved creep-rupture strength**
  - **Needs data for ASME code submission**
  - **Not practical for plant site erection**



Tortorelli, et al, ORNL

Seam Welded Pipe

Justification

- Cost 40% lower than seamless where technically feasible
- Higher productivity and capacity
- Demonstration under Gen 3, CSP program

Trials

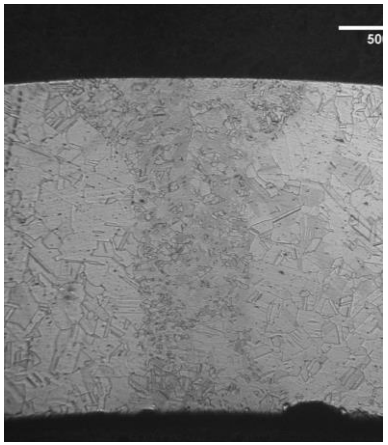
- Fabrication at Swepco Tube Co
- 44” W x 240” L x ¾” T 740H plate
- Cold formed into 14” OD pipe
- GTA weld (740H filler, 8 passes)
- Solution anneal and age
- No rejectable indications
- Pass bend, tensile per CC 2702
- Creep testing underway

Steps in the pipe forming operation at Swepco

740H pipe welding at Swepco

Seam Welded Tube

- 0.065” T strip rolled at Special Metals
- Laser welded at RathGibson
- In-line anneal and eddy current
- Off-line continuous anneal
- Partial recrystallization of weld metal
- Tensile and burst tests met CC 2702 requirements
- Cold tube bending
- Automated welding procedure development



Weld structure

Finished tubes

Bends, Tebunus Tube Bending, NL

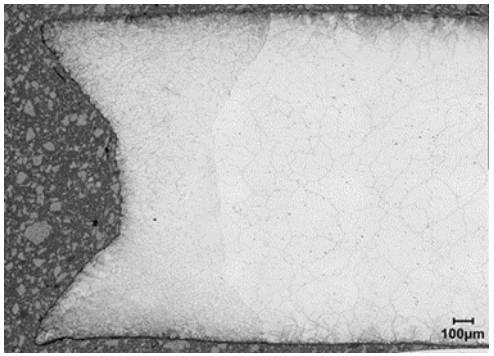
Burst test, RathGibson, North Branch, NJ

Automated butt welds, Liburdi

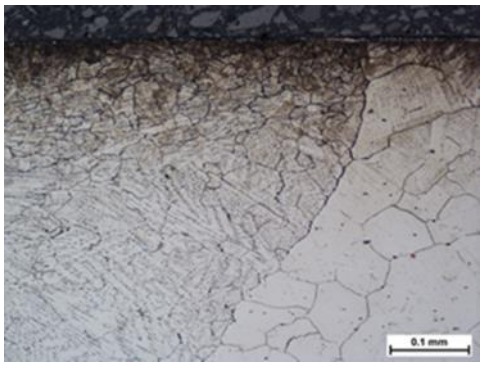
Welded and Redrawn Tubes

- **Creep-rupture test results on welded tube**
  - EPRI developed internally pressurized creep test
  - Premature failure
  - Crack follows fusion line
  - Reanneal did not improve
- **Redrawing welded tube**
  - Commonly used for specialty tube
  - Adds about 10% to cost
  - Two trials completed
  - Rupture life greatly improved
- **% cold work trials**
  - Define minimum reduction for ASTM spec
  - No general standard exists
  - Tube drawing underway

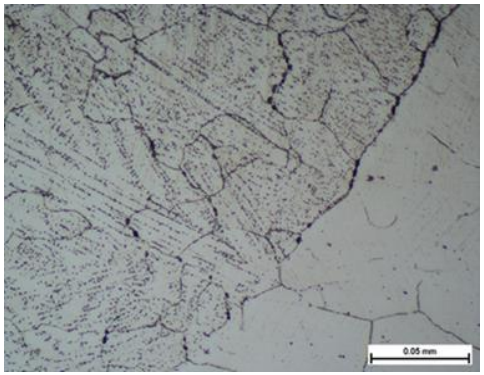
Fracture path across tube wall



Fusion line crack



Some voids in weld metal



Dissimilar Metal Welds

740H will be welded to another alloy!

In hot zone

- 740H to 282 Casting with 282 FM (ORNL)
- 740H to 617 with 617 FM
- 740H fabrication or repair with 263 SMAW
- Finned tube – 304 Resistance welds

Outside hot zone

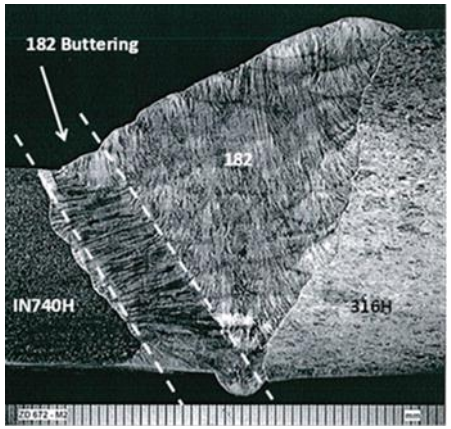
- 740H to austenitic stainless with 82 FM
- 740H to ferritic stainless with 82 FM

Considerations

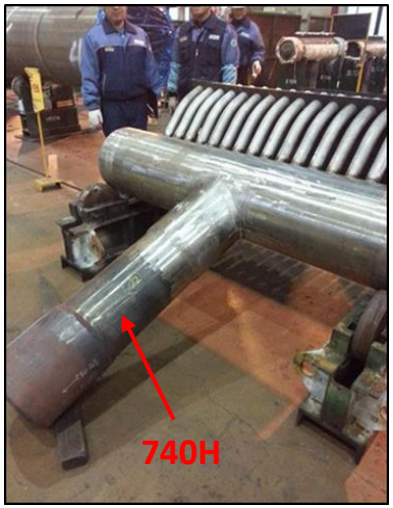
- Compatibility with PWHT cycle
- Chemical compatibility
- Dilution effects
- Long time microstructure stability
- Coefficient of Thermal Expansion

740H butt welded to Sanicro 25

304 SS fins on 740H tube (Optimus)



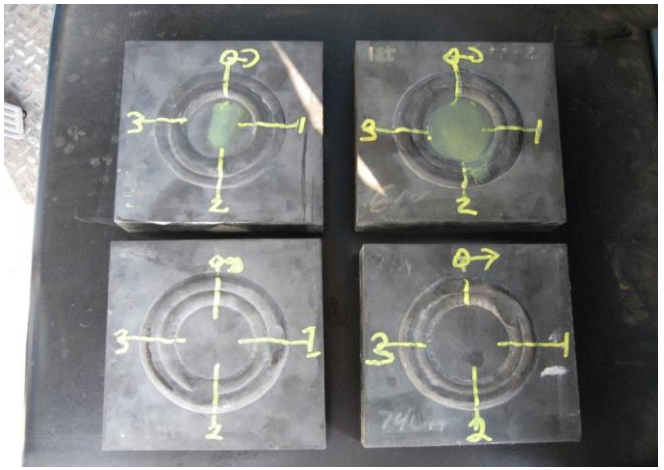
Butter layer to avoid overheating 316



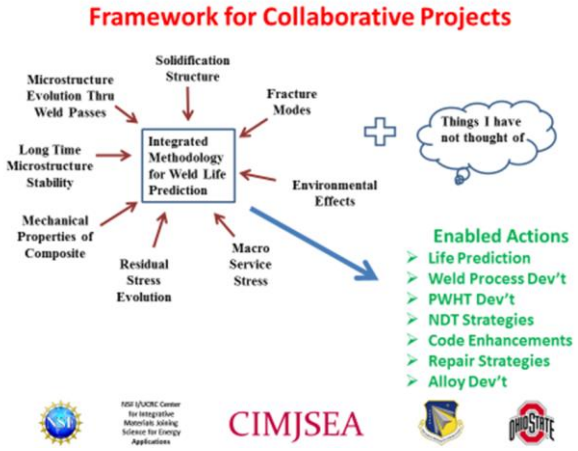
Transition Joint

What Remains to be Done

- Refine procedures and communicate
  - EPRI contract
- Stress relaxation cracking
  - Programs at Lehigh University
  - Quantifying strain-age cracking
  - Experimental vs modeling
  - Characterizing damage tolerance
- Complete code activity
  - Recalculate stress allowables
  - Solution annealed welds
  - Section VIII
- Mechanical fatigue, thermal fatigue, creep fatigue, corrosion fatigue of base metal and weldments
- Damage tolerance, inspection and repair welding



Borland test – one type of SRC test



Modeling will be difficult due to the many moving parts

Acknowledgements

Portions of this work were supported through US DOE Awards DE-FE0025064nand DE-EE0008367