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National Energy Technology Laboratory

Welding of Dissimilar Alloys for High Temperature Heat Exchangers for SOFC

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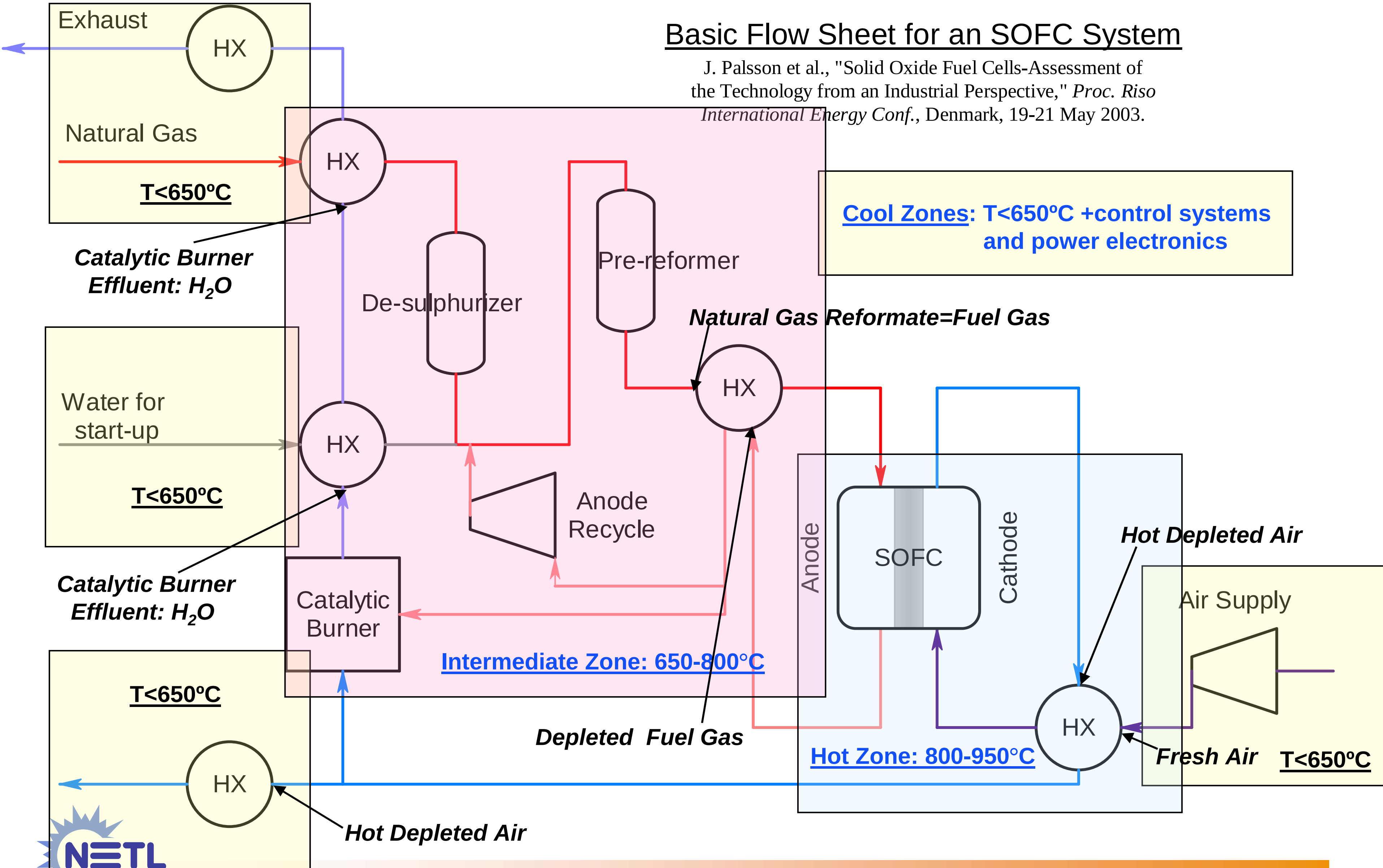
Solid Oxide Fuel Cell Systems

- High temperature heat exchangers are a cost enabler in order to meet the stated Solid State Energy Conversion Alliance (SECA) requirements of $400/kW

Basic Flow Sheet for an SOFC System

J. Palsson et al., "Solid Oxide Fuel Cells-Assessment of the Technology from an Industrial Perspective," *Proc. Riso International Energy Conf.*, Denmark, 19-21 May 2003.



Low-Cost High-Temperature Heat Exchangers

Develop low-cost, high-temperature heat exchangers for cathode air preheaters for use in 3-10kW SOFC systems.

- **Source: Post-combustor SOFC stack effluent with inlet temperatures of 800-1000ºC.**
- **Sink: Air from cathode air blower (30ºC)**
- **Flow rate: Both source and sink at 1500 slpm max.**
- **Differential pressure drop: sink 1.5-2.5kPa, source 0.75-1.25kPa**
- **Effectiveness: 85-90%**
- **Design life: 40,000 hours**

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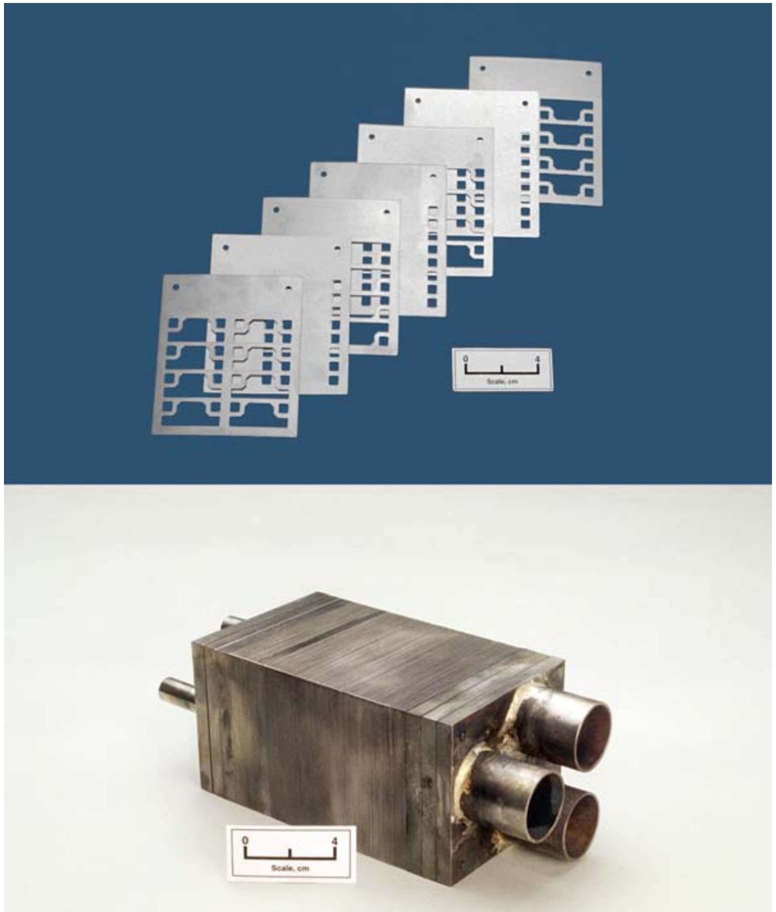
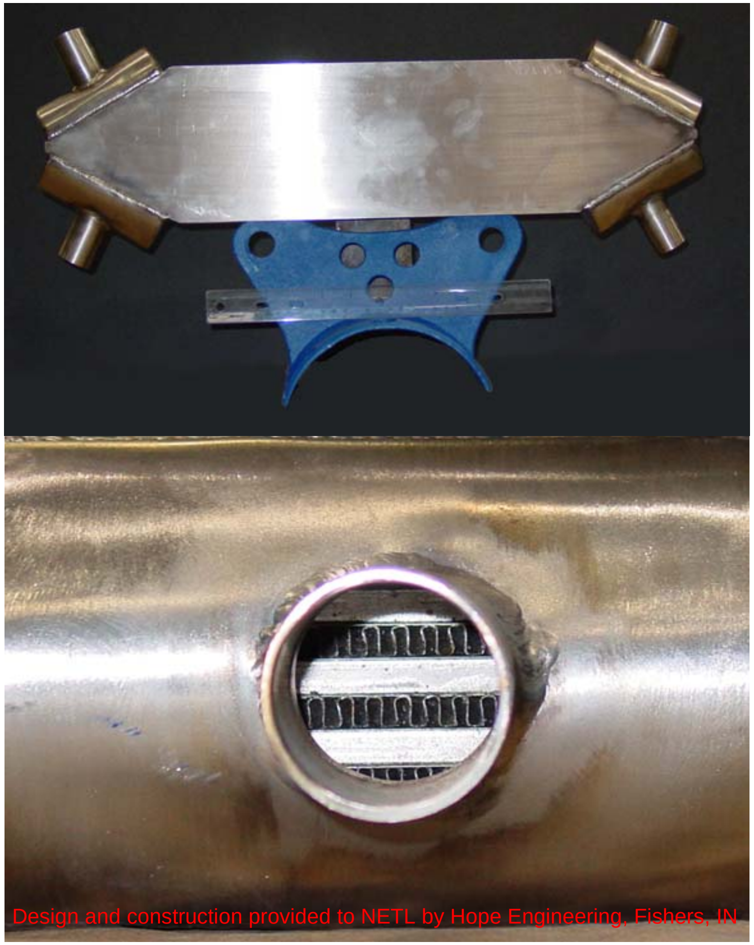
Comparison of Heat Exchanger Types

Micro-Channel
Heat Exchangers



Design and construction by Wilson and Alman, U.S. Dept. of Energy, National Energy Technology Center (formerly the Albany Research Center)

Plate-Fin
Heat Exchangers

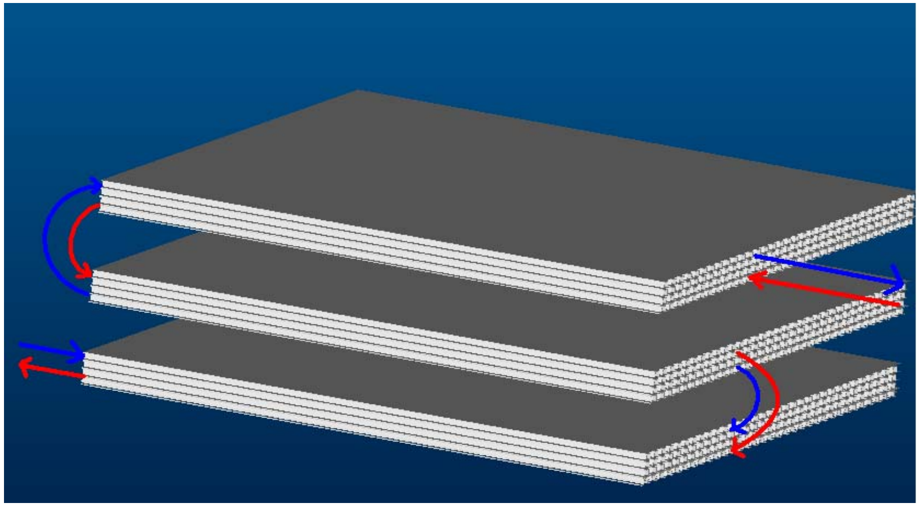


Design and construction provided to NETL by Hope Engineering, Fishers, IN

Modifying the Design to Reduce Material Costs

- Modifying the flow design could allow extreme temperatures to be isolated to specific regions of the heat exchanger.

- The regions subjected to lesser thermal extremes could then be made from cheaper materials.



Investigation of Dissimilar Metal Welding

Objectives

- To predict weld phases using equilibrium and kinetic calculations and verify them using experimental techniques such as SEM, XRD, optical microscopy.
- To predict welding defects that may cause failure using simulations and experimental techniques.
- To select steel and filler metal compositions based on knowledge gained above.

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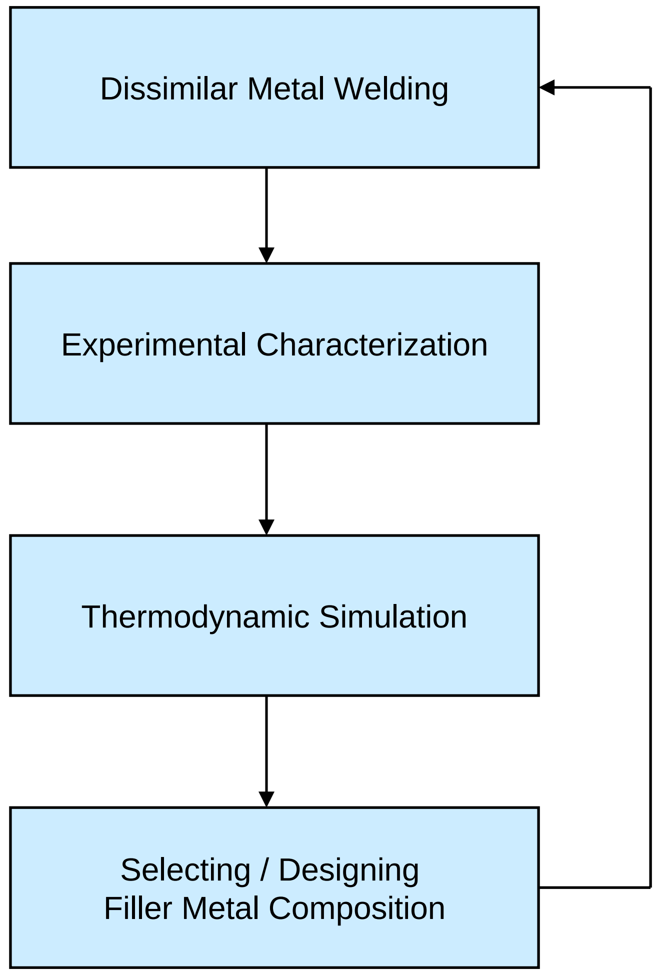
Approach

- Experimental characterization of welds and defects
- Thermodynamic modeling of mixed zones in dissimilar metal welds


Dissimilar Metal Welding
Experimental Characterization
Thermodynamic Simulation
Selecting / Designing
Filler Metal Composition

Dissimilar metal welding

- **We have looked at 10 combinations of materials for welding:**

1.	IN625	and	347SS	with E347
2.	IN625	and	409SS	with E410
3.	IN625	and	AL 20-25+Nb	with E309L
4.	347SS	and	409SS	with E309L
5.	347SS	and	AL 20-25+Nb	with E309L
6.	AL 20-25+Nb	and	409SS	with E309L
7.	AL 20-25+Nb	and	AL 20-25+Nb	with E309L
8.	IN625	and	409SS	with ENiCrMo3
9.	AL 20-25+Nb	and	AL 20-25+Nb	with ENiCrMo3
10.	AL 20-25+Nb	and	AL 20-25+Nb	with E347

Welding

- Gas tungsten arc welding (GTAW) process
- The welding parameters were 132 amperes, 13 volts and 10.16 mm per minute welding speed
- The weld specimens were 15.24 cm long 19.05 mm wide and 6.35 mm thick
- The welds were approximately 50.8mm long and 3.175 mm deep
- Welds were made on both sides of the specimens to try to produce full penetration weld at the center of the weld specimens

Dissimilar metal welding

- **4 combinations showed defects in as welded conditions**

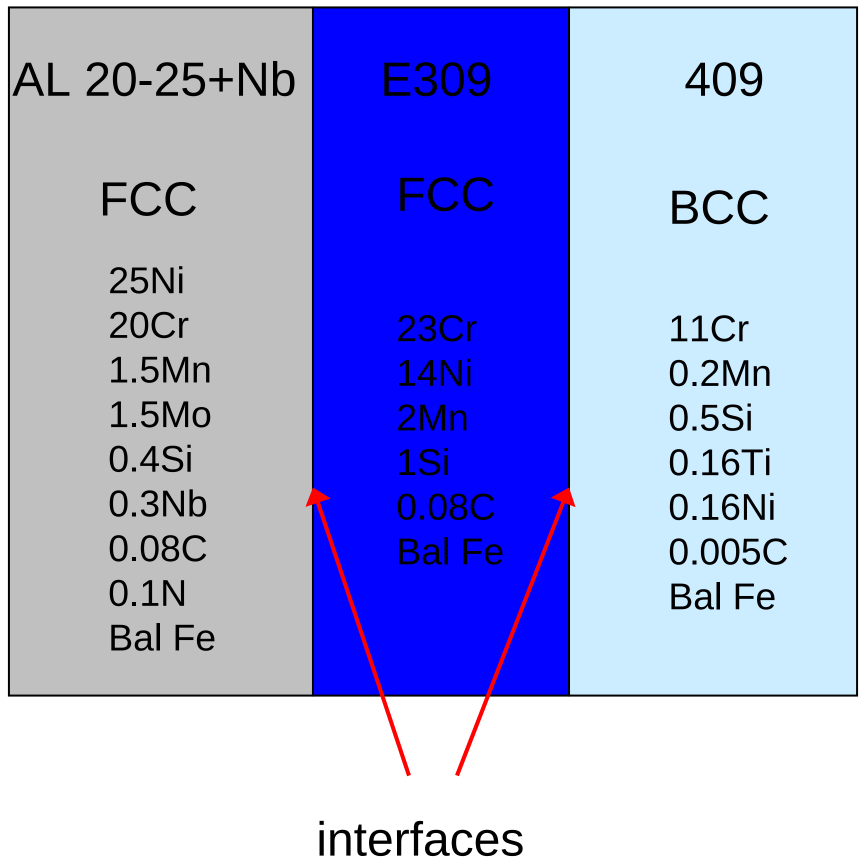
1. IN625	and	347SS	with E347	
2. IN625	and	409SS	with E410	HAZ cracking
3. IN625	and	AL 20-25+Nb	with E309L	
4. 347SS	and	409SS	with E309L	
5. 347SS	and	AL 20-25+Nb	with E309L	Hot cracking
6. AL 20-25+Nb	and	409SS	with E309L	HAZ cracking
7. AL 20-25+Nb	and	AL 20-25+Nb	with E309L	Hot cracking
8. IN625	and	409SS	with ENiCrMo3	
9. AL 20-25+Nb	and	AL 20-25+Nb	with ENiCrMo3	
10. AL 20-25+Nb	and	AL 20-25+Nb	with E347	

Dissimilar metal welding

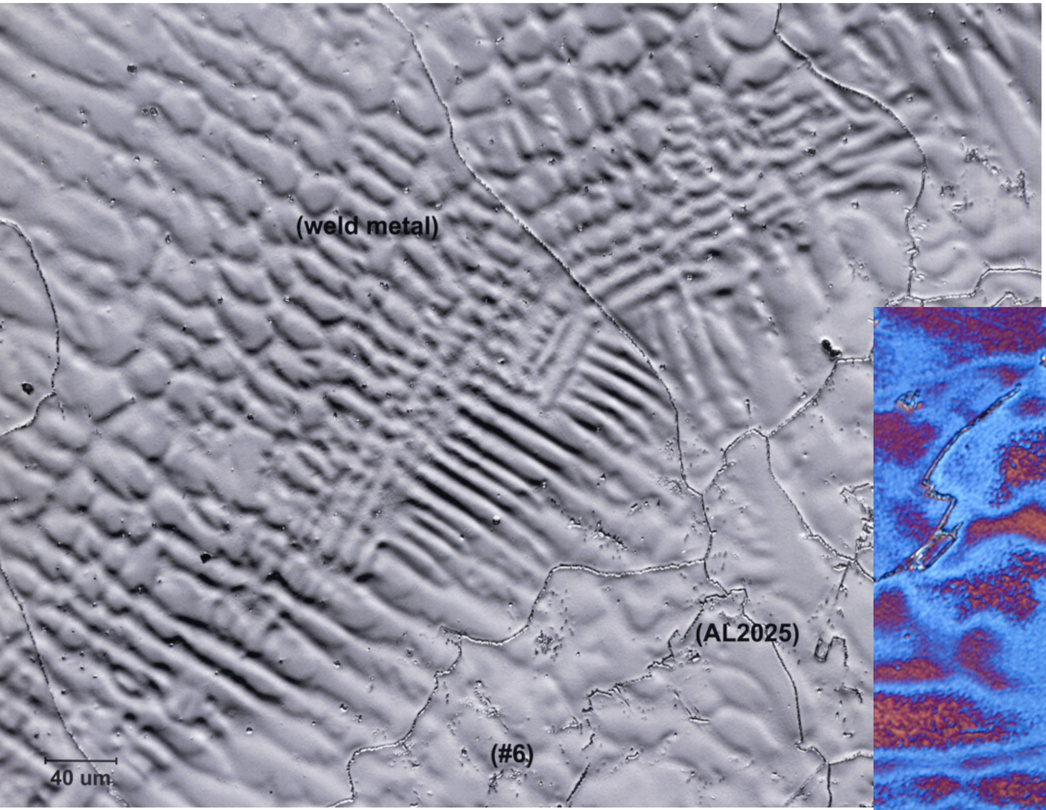
- **We heat treated 7 welds at 800ºC up to 2000 hours**

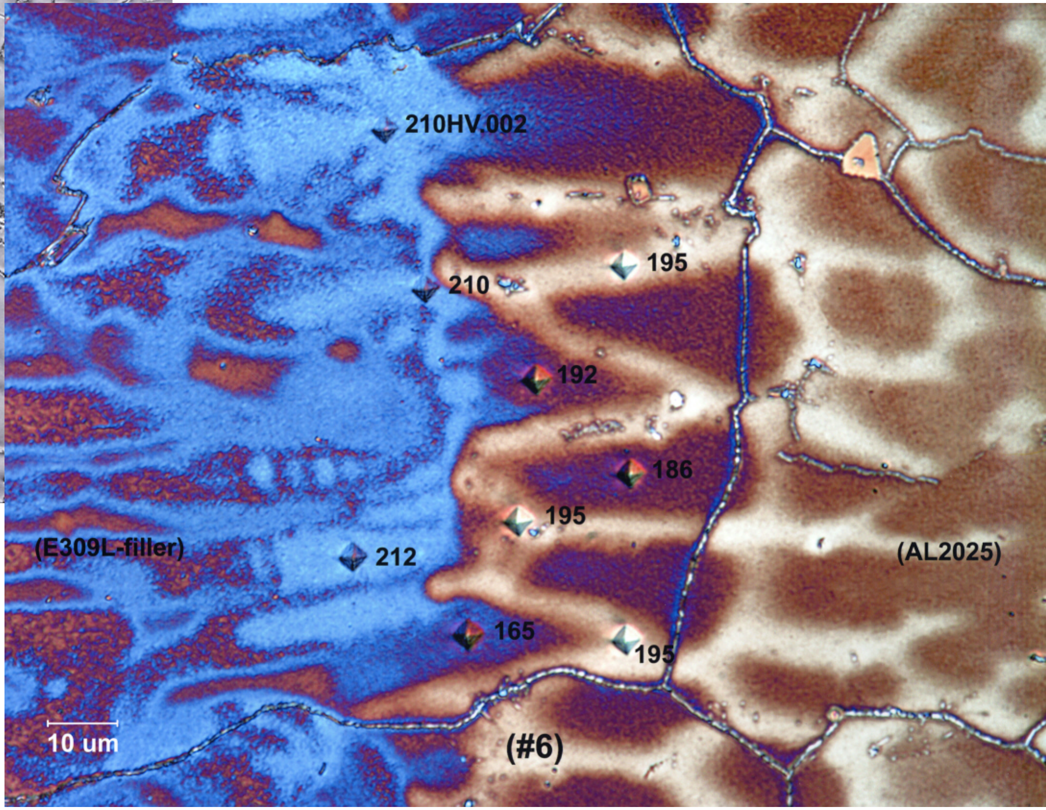
1.	IN625	and	347SS	with	E347
2.	IN625	and	409SS	with	E410
3.	IN625	and	AL 20-25+Nb	with	E309L
4.	347SS	and	409SS	with	E309L
5.	347SS	and	AL 20-25+Nb	with	E309L
6.	AL 20-25+Nb	and	409SS	with	E309L
7.	AL 20-25+Nb	and	AL 20-25+Nb	with	E309L
8.	IN625	and	409SS	with	ENiCrMo3
9.	AL 20-25+Nb	and	AL 20-25+Nb	with	ENiCrMo3
10.	AL 20-25+Nb	and	AL 20-25+Nb	with	E347

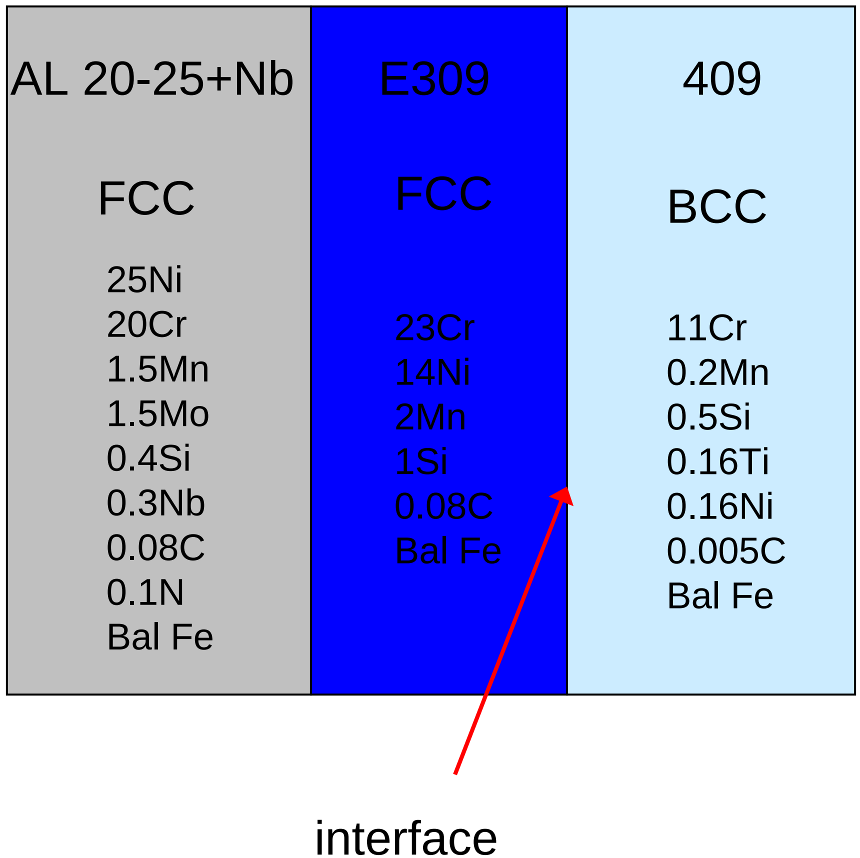
Welding dissimilar alloys

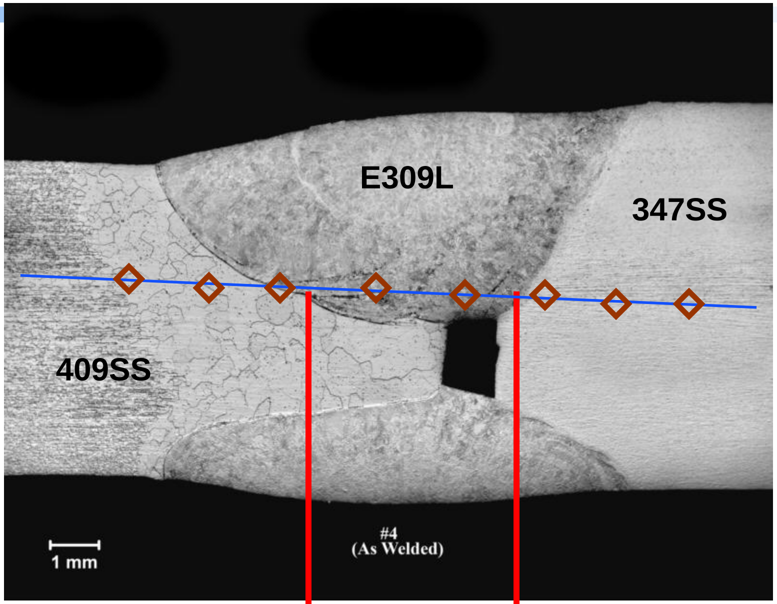


Interface between AL 20-25+Nb and E309

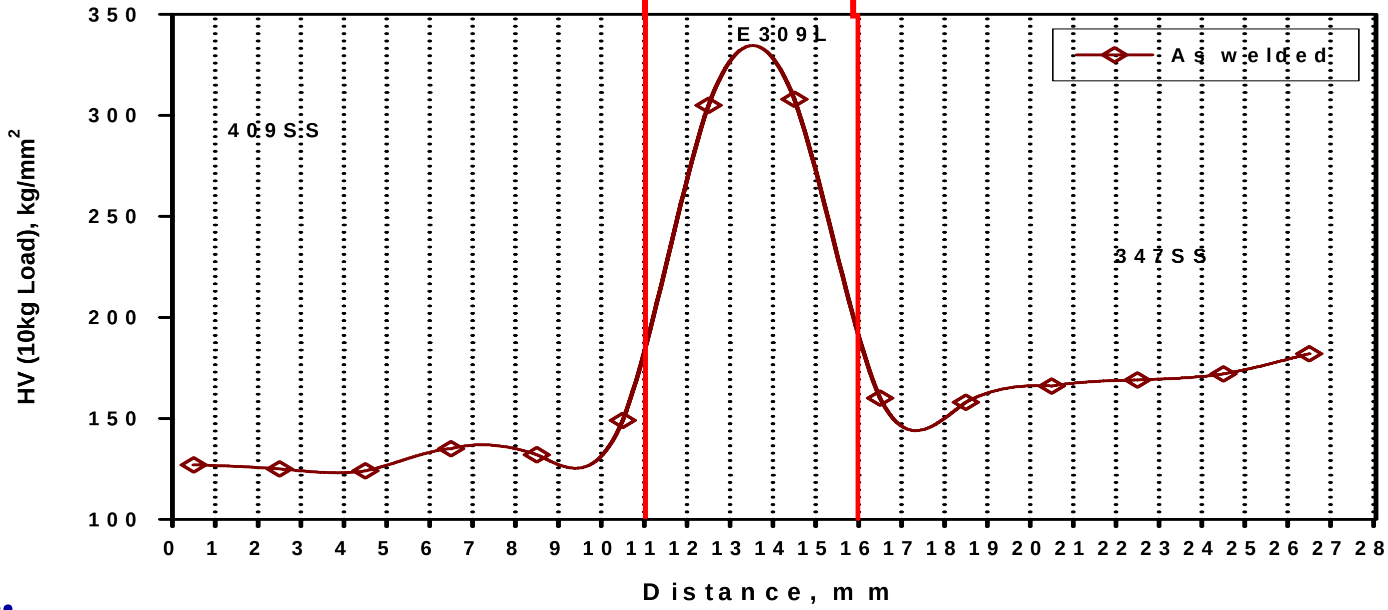





AL 20-25+Nb
FCC
25Ni
20Cr
1.5Mn
1.5Mo
0.4Si
0.3Nb
0.08C
0.1N
Bal Fe
E309
FCC
23Cr
14Ni
2Mn
1Si
0.08C
Bal Fe
409
BCC
11Cr
0.2Mn
0.5Si
0.16Ti
0.16Ni
0.005C
Bal Fe
interface

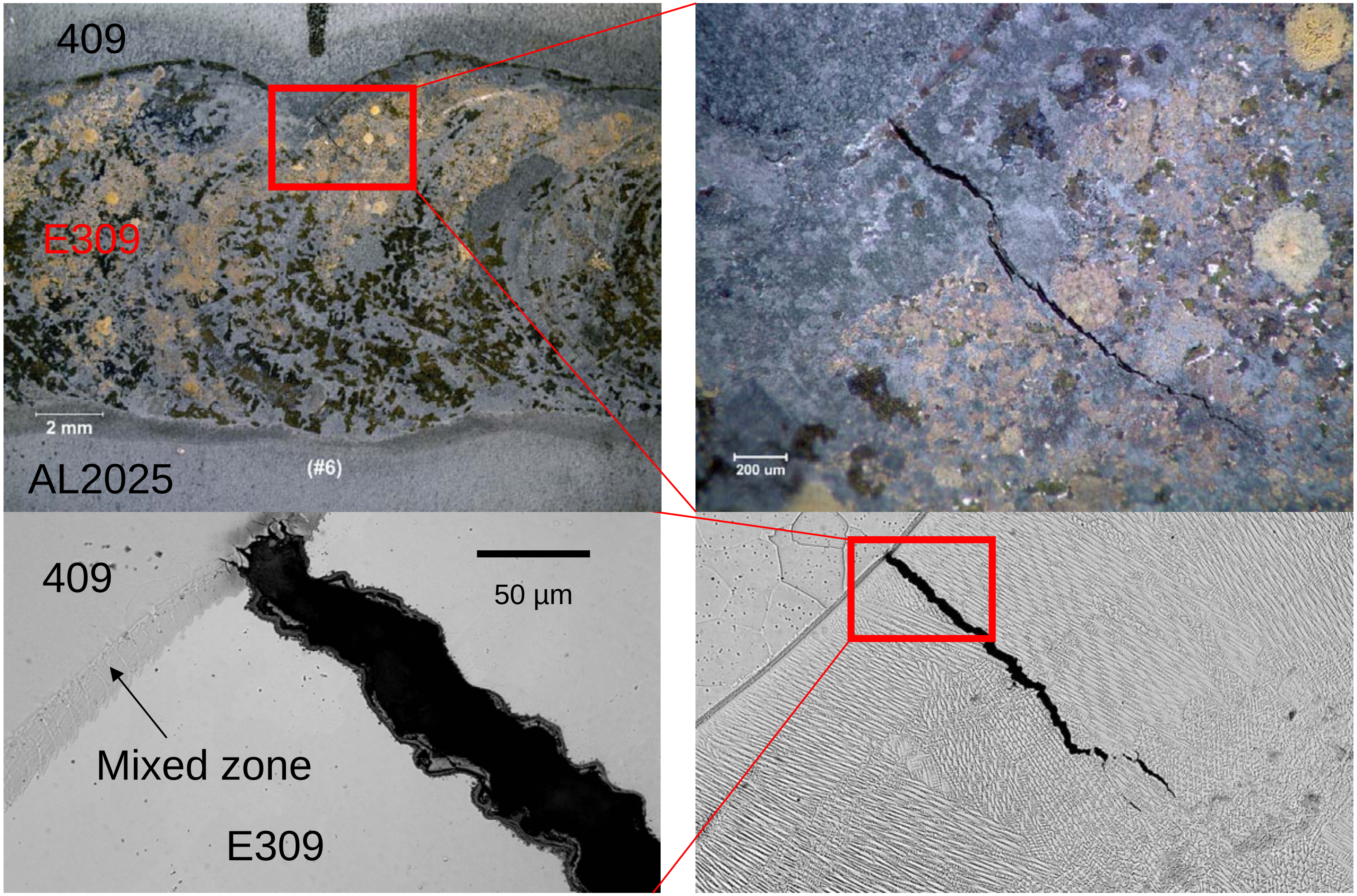


E309L
347SS
409SS
1 mm
#4
(As Welded)



HV (10kg Load), kg/mm^2
Distance, mm
As welded
409SS
E309L
347SS
350
300
250
200
150
100
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28

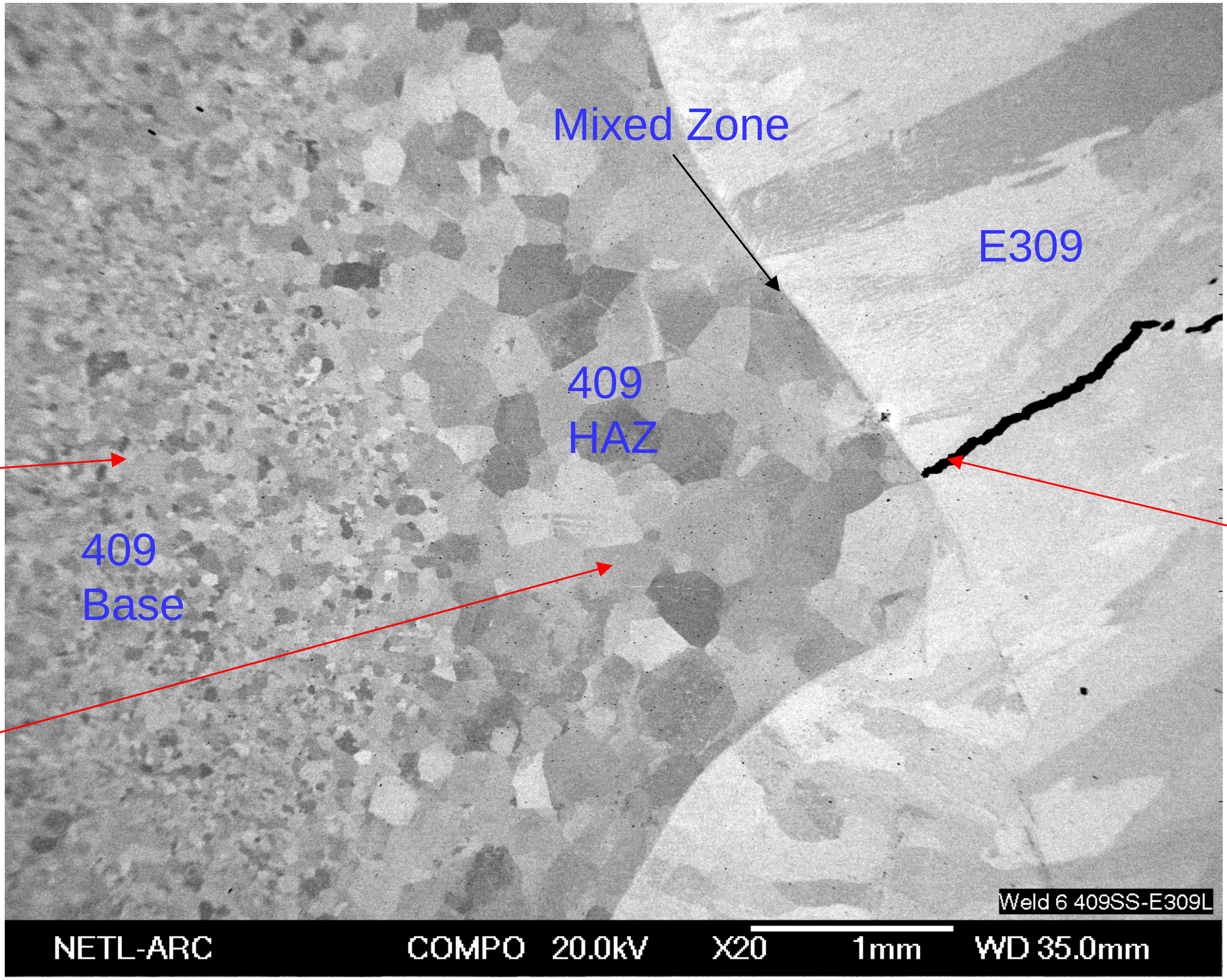
Weld cracks originating from the mixed zone



Mixed Zone Experimental Characterization

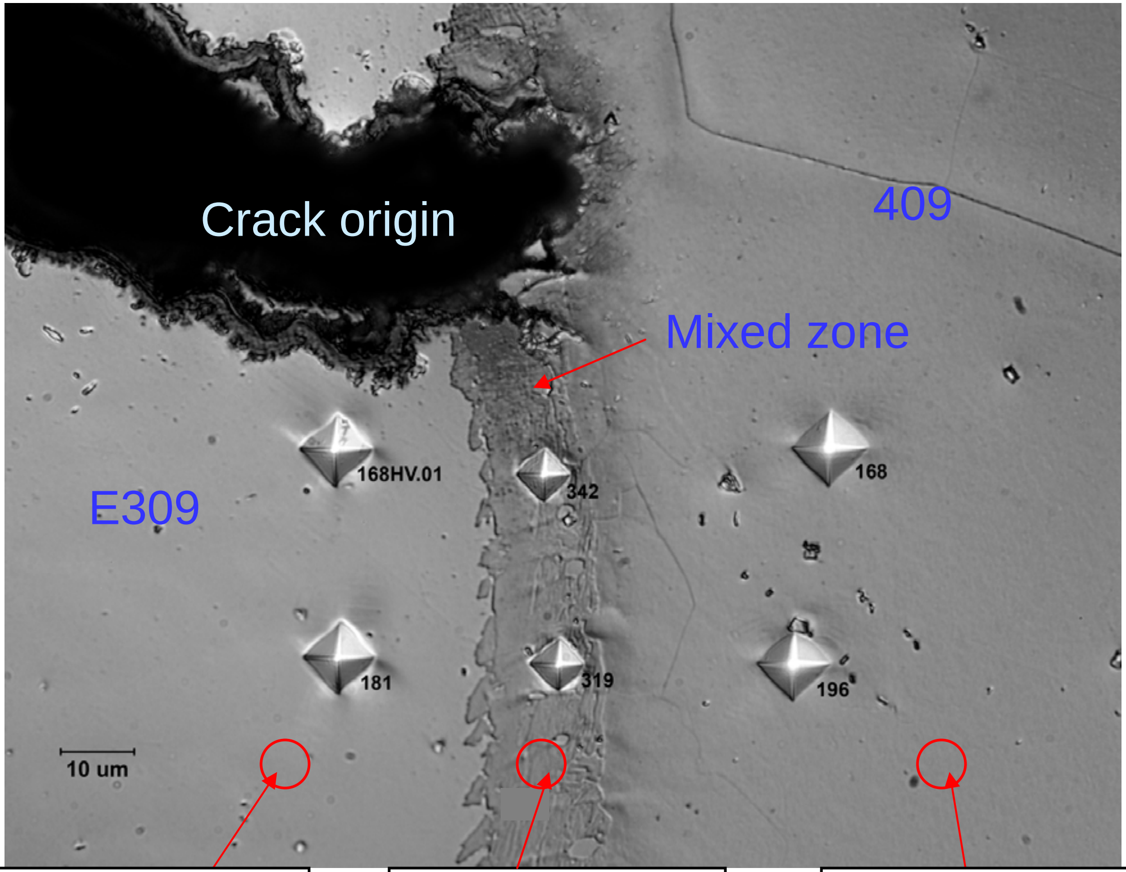
Small grain size

Large grain size



Crack

Mixed Zone Experimental Characterization

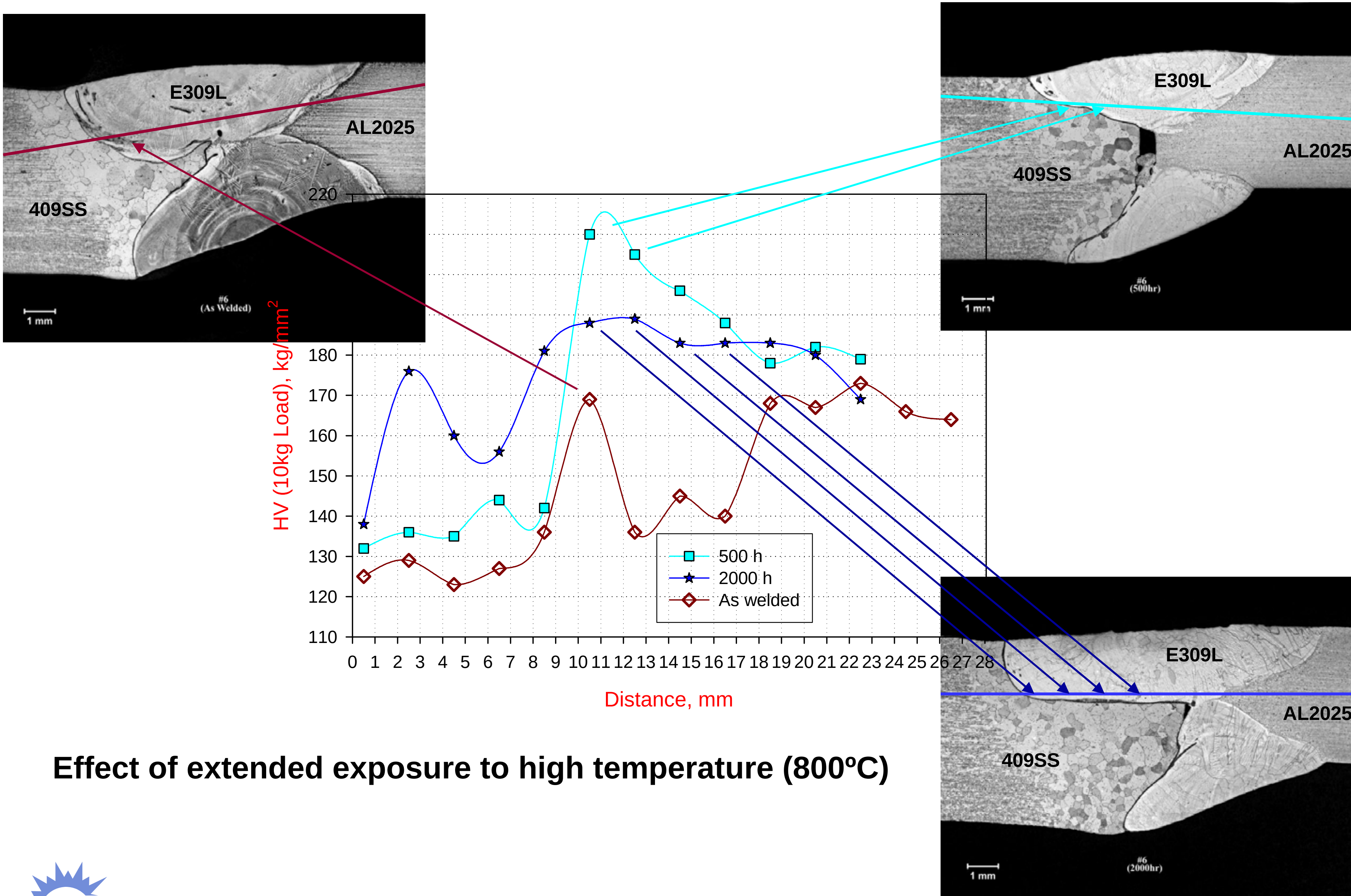


Fe-17Cr-12Ni-1Mn-0.8Si-0.5Mo-0.08C

Fe-14Cr-3Ni-0.6Mn-1Si-0.1Ti-0.01Nb

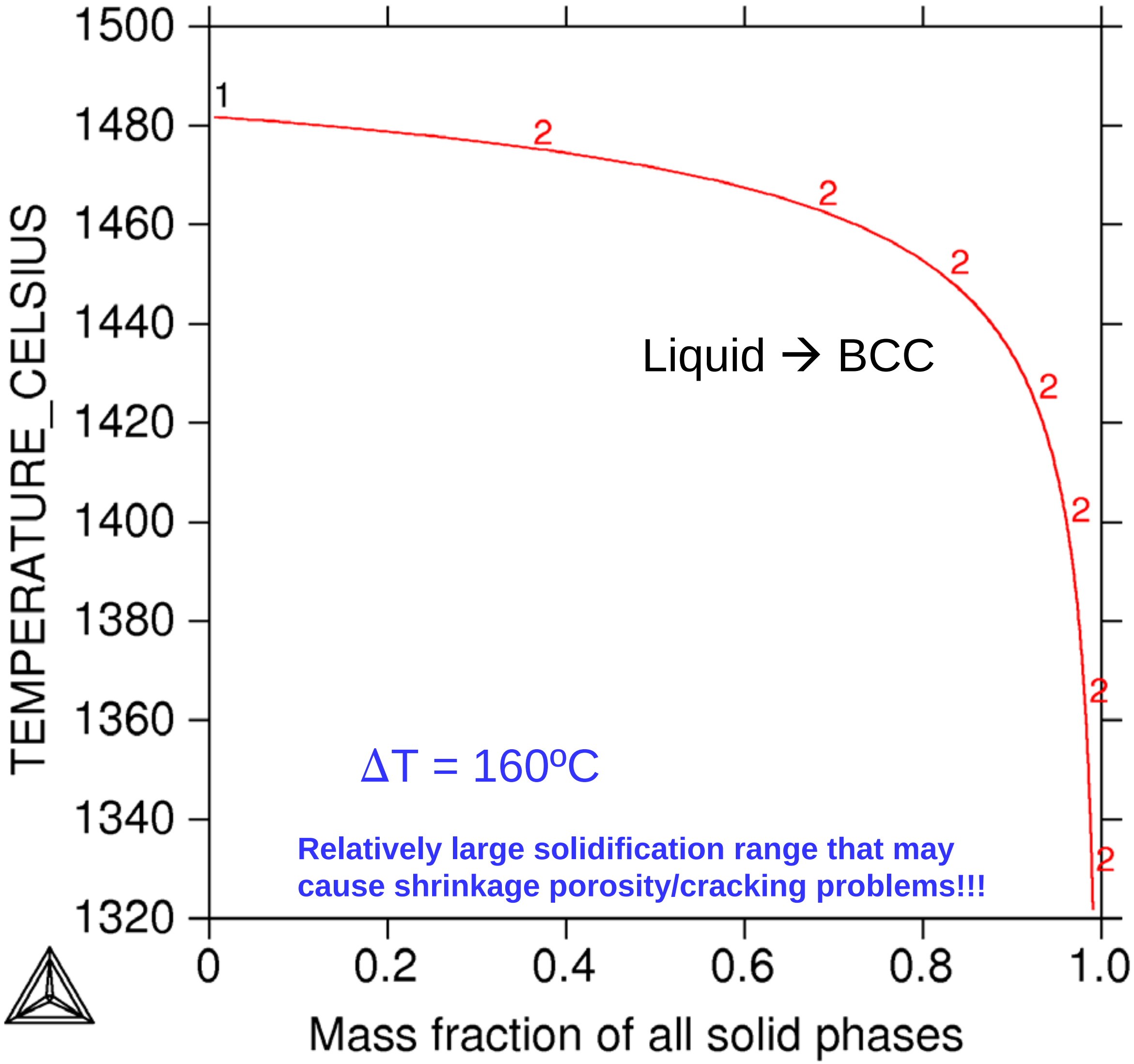
Fe-12Cr-0.3Ni-0.5Mn-1.2Si-0.1Ti-0.01C

Compositions were determined by SEM-WDX



Effect of extended exposure to high temperature (800ºC)

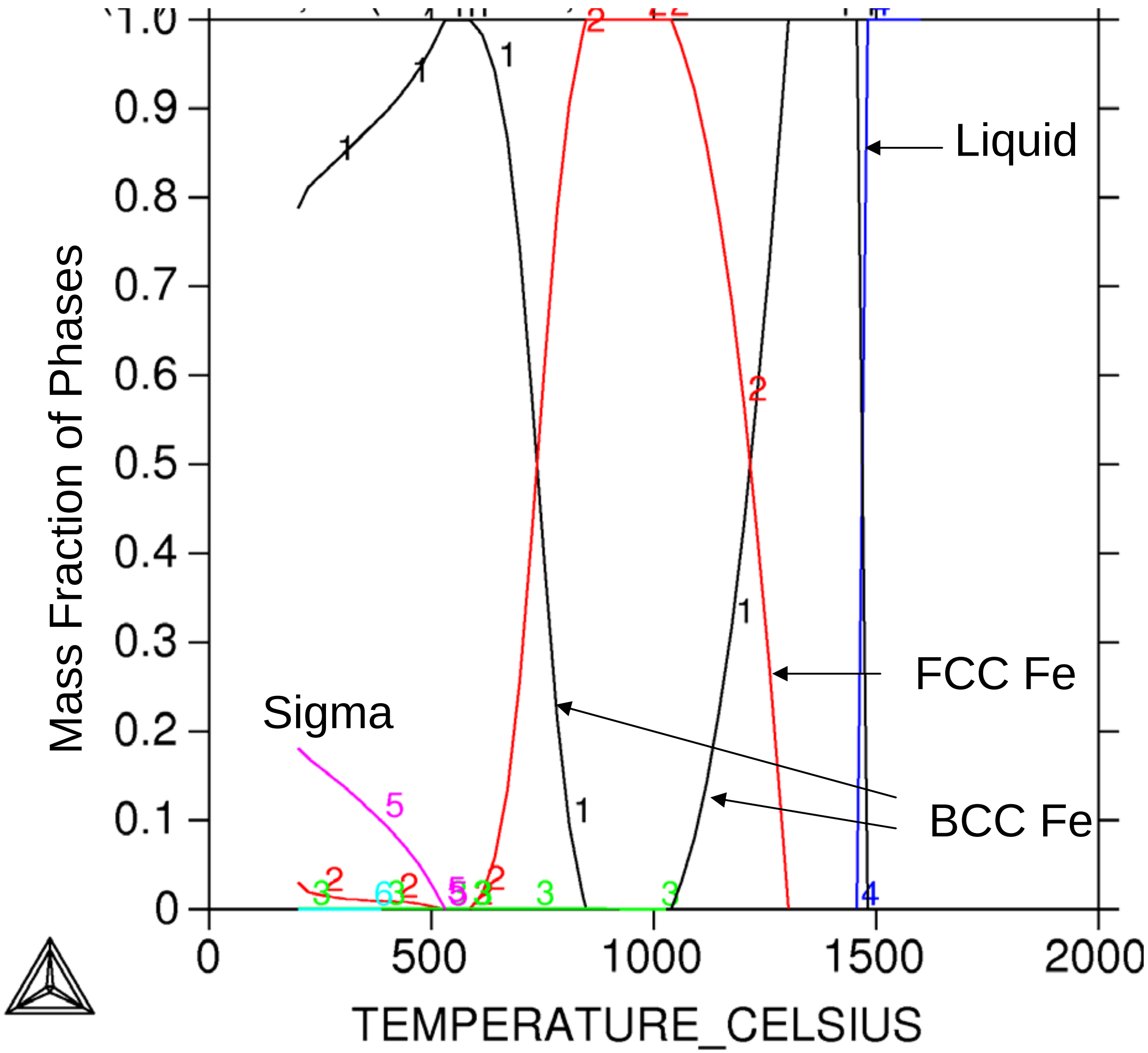
Scheil simulation of the mixed zone



Composition
Mass%

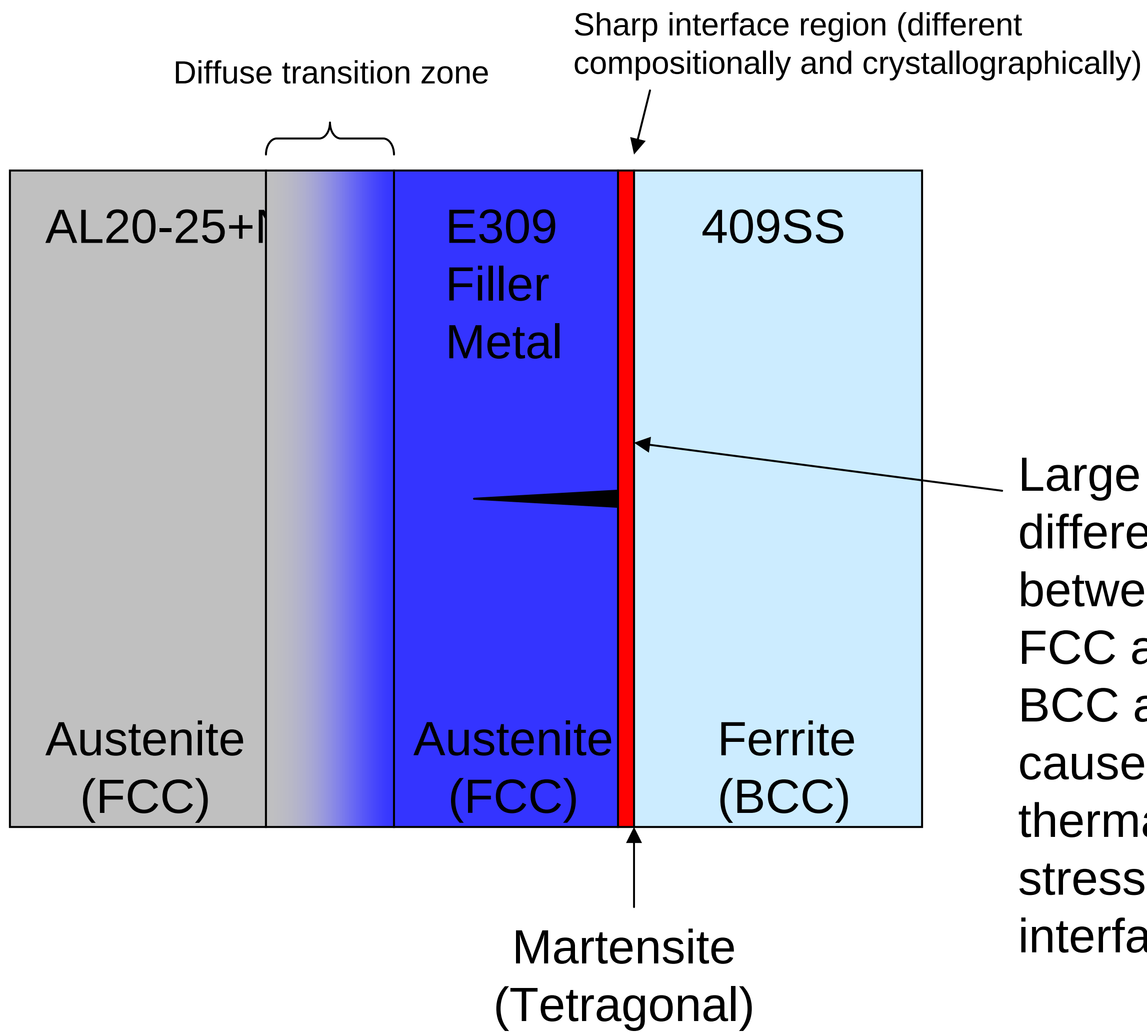
Fe Bal.
Cr 14
Ni 3
C 0.01
Mn 0.6
Si 1
Ti 0.1
Nb 0.01

Calculated equilibrium phases in the mixed zone between 409 and filler metal (E309)



Composition
Mass%

Fe Bal.
Cr 14
Ni 3
C 0.01
Mn 0.6
Si 1
Ti 0.1
Nb 0.01



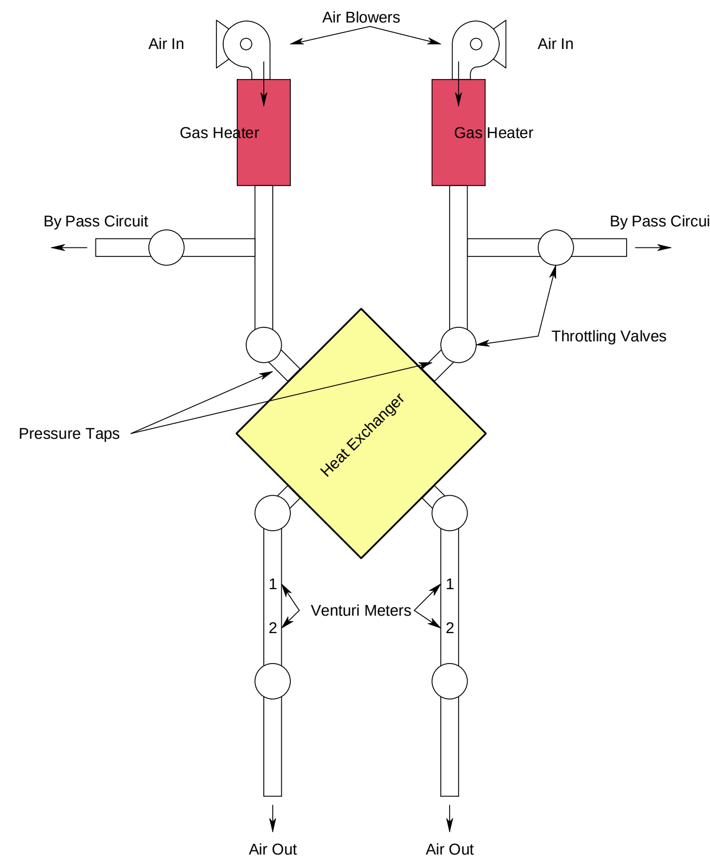
Large CTE differences between FCC and BCC alloys cause thermal stresses at interfaces

Selecting / Designing Filler Alloy

- **Based on the experimental characterization of welds and thermodynamic simulation, a high Cr (>20 mass%) ferritic steel containing no Ni was selected as filler alloy for the next iteration.**

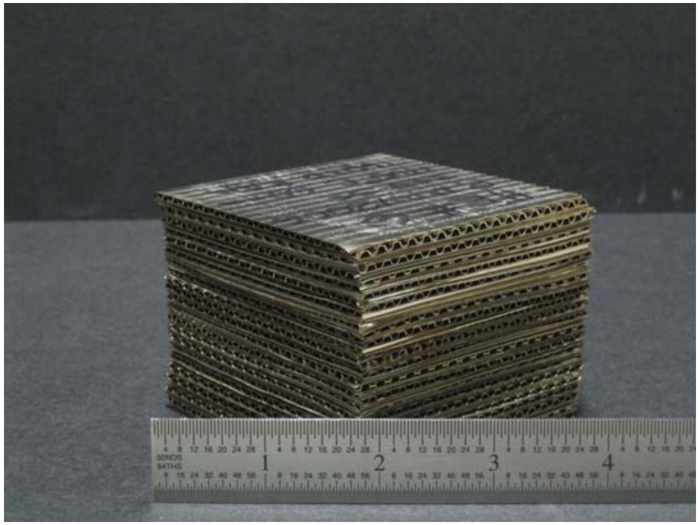
Heat Exchanger Test Facility at NETL

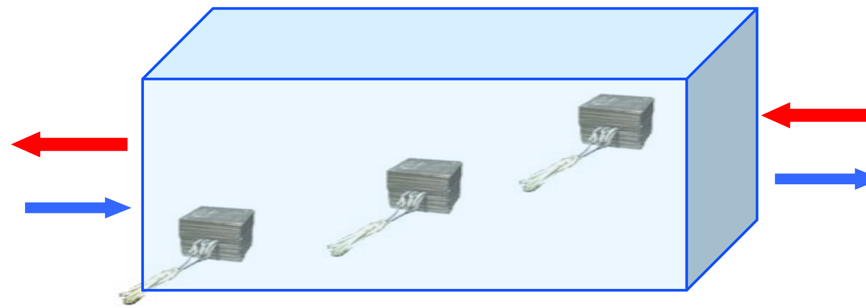
- **Design Criteria**
  - Dual atmosphere construction
  - 100-300 lbs/hr flow at 2.9 psig
  - Temperature range of hot side is 1000F-1650F (650-1000 C)
  - Temperature range of cold side is ambient to 600 F (25-300 C)
  - Heater design pressure to 4 psig
  - Natural gas fired (both hot and cold side)



SOFC HX Test Stand

Testing of Heat Exchangers





HX investigation utilizing HX "elements" to investigate materials performance at the different conditions encountered in high temperature HX

Summary

- Reducing material cost of high temperature heat exchangers can help to reduce the cost of SOFC systems.
- Less expensive materials can be used in lower temperature regions of heat exchangers while the highest temperature parts are built using costly superalloys.
- Dissimilar metal welding issues need to be addressed in order to built heat exchangers using several different alloys.

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Summary continued

- **In this presentation, we demonstrated how a thermodynamic simulation method can be utilized along with experimental methods to select or design filler metals for dissimilar metal welding.**