Sandia National Laboratories
THE OHIO STATE UNIVERSITY
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Selective Element Vaporization during Laser Rewelding of 304L Alloys with Controlled Manganese Levels

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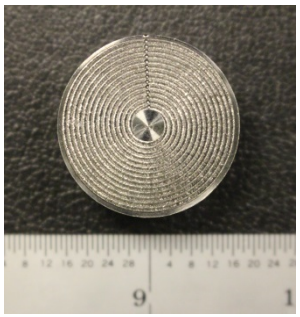
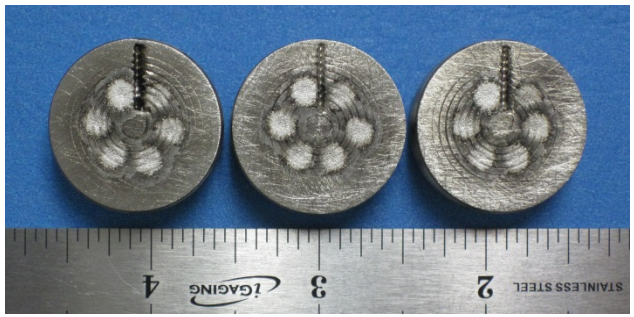
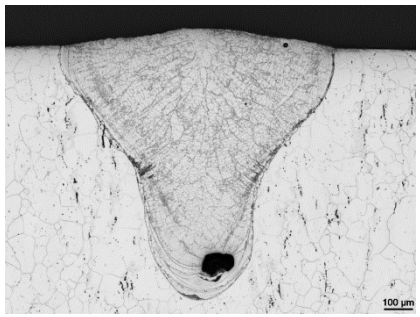
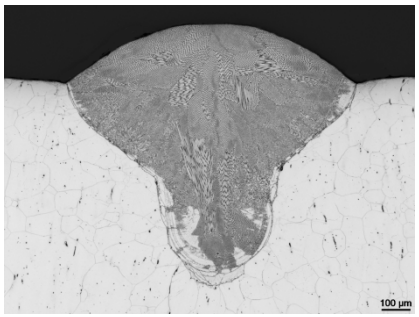




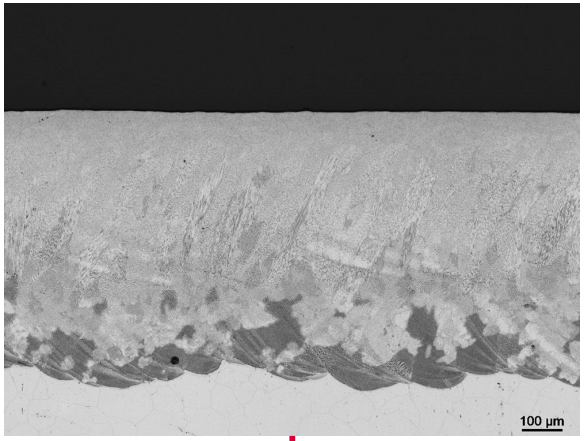




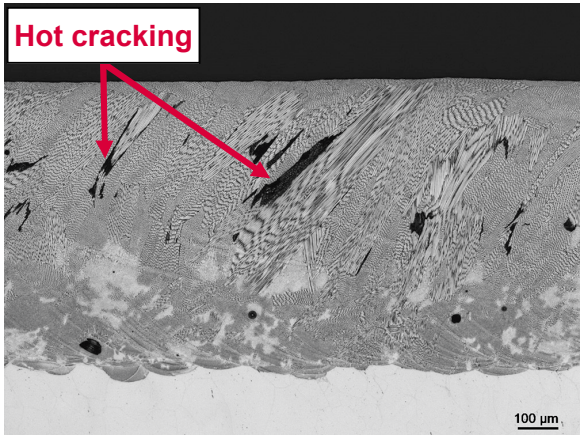
Motivation

- Hot cracking in weld termination overlap region of prototype weld assembly
- Need an engineering tool to define component rewelding limits
- Mn known to be a high vapor pressure element
- Desire to understand effect of Mn level on bulk vaporization behavior

Continuous wave 1X weld region



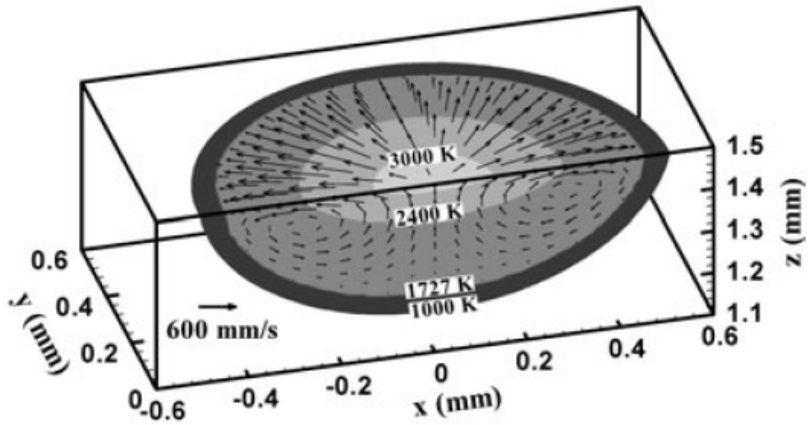
Continuous wave 6X weld region



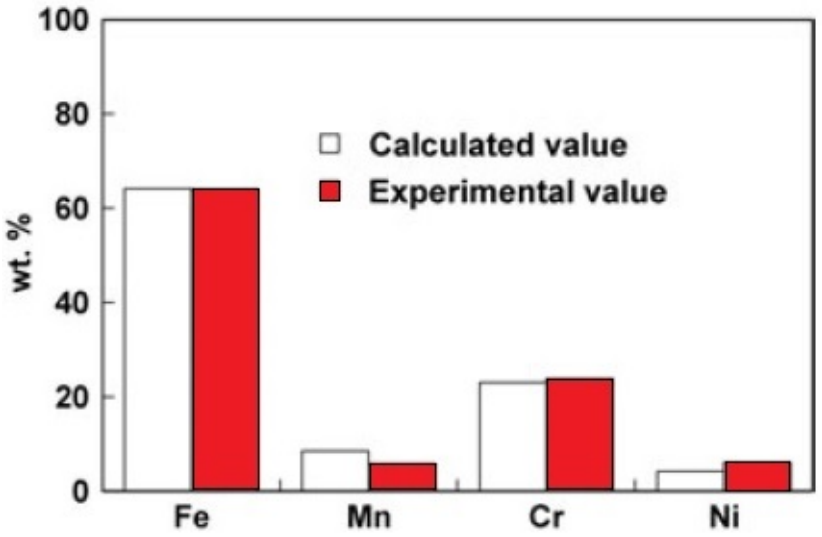
Physical Vaporization Model

- Vaporization during laser welding well known
- Pressure and composition driven vaporization
- Well tested physical model

Weld pool temperature and velocity distribution



Vapor composition during welding



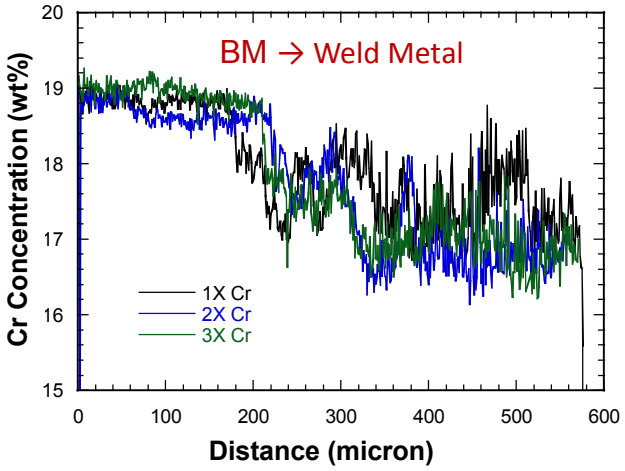
X. He, P.W. Fuerschbach, & T. DebRoy
J. Appl. Phys. **94** (2003) 6949-6958.

SNL Vaporization Study

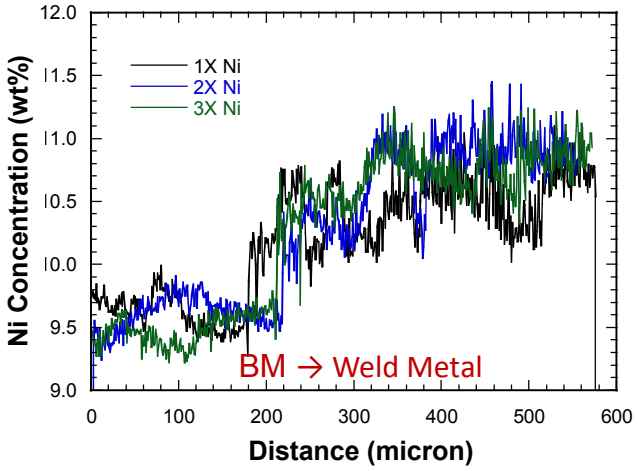
- Rewelding of VAR 304L
- Verified vaporization behavior
- Investigated solidification mode evolution and solidification cracking behavior

Pulsed Weld EPMA Scans

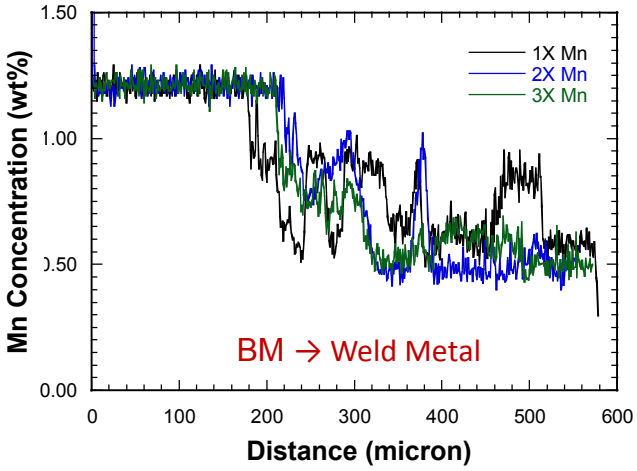
Chromium



Nickel



Manganese



Experimental Alloys

- 304L "like" alloys with controlled levels of Mn and Cr_{eq}/Ni_{eq}

Target Compositions (wt%)

	Alloy 1	Alloy 2	Alloy 3	Alloy 4	Alloy 5
Cr	19.10	19.10	19.10	19.10	19.10
Mo	0.10	0.10	0.10	0.10	0.10
Si	0.57	0.57	0.57	0.57	0.57
Ni	11.13	10.98	10.82	10.70	10.54
Mn	0.70	1.20	1.70	2.10	2.60
C	0.005	0.005	0.005	0.005	0.005
N	0.005	0.005	0.005	0.005	0.005
Cu	0.15	0.15	0.15	0.15	0.15
P	-	-	-	-	-
S	-	-	-	-	-
Fe	68.2	67.9	67.6	67.3	66.9
Cr_{eq}/Ni_{eq}	1.72	1.72	1.72	1.72	1.72

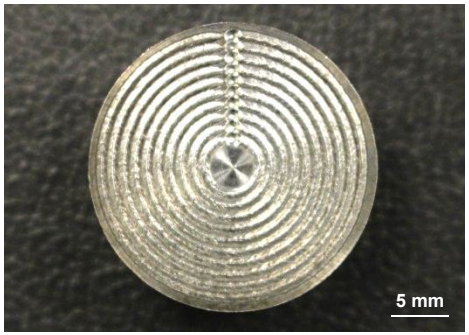
As Fabricated Compositions (wt%)

	Alloy 1	Alloy 2	Alloy 3	Alloy 4	Alloy 5
Cr	18.99	19.06	19.15	19.11	19.02
Mo	0.10	0.10	0.095	0.10	0.10
Si	0.58	0.59	0.56	0.57	0.57
Ni	11.19	11.03	10.77	10.68	10.58
Mn	0.67	1.13	1.58	1.98	2.46
C	0.011	0.0060	0.0065	0.0077	0.0065
N	0.0024	0.0019	0.0027	0.0025	0.0027
Cu	0.11	0.11	0.13	0.13	0.12
P	<0.005	<0.005	<0.005	<0.005	<0.005
S	0.002	0.002	0.003	0.003	0.003
Fe	68.3	67.9	67.7	67.3	67.1
Cr_{eq}/Ni_{eq}	1.70	1.72	1.74	1.73	1.72

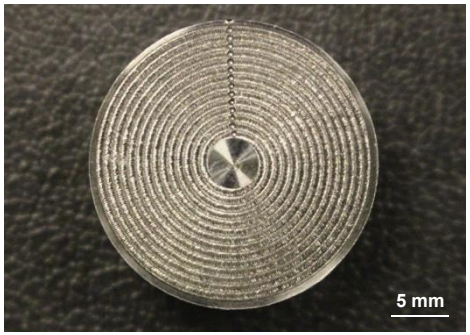
Seam Welding Procedures

- **Continuous Wave (CW) Parameters:** P = 500 W, s = 80 ipm (2.03 m/min)
  - Reweld conditions: 1X, 2X, 3X, 6X, 9X, 12X
- **Pulsed Parameters:** P_p = 612 W, t = 12 ms, s = 1.5 ipm (0.04 m/min), f = 4 Hz
  - Reweld conditions: 1X, 2X, 3X, 6X

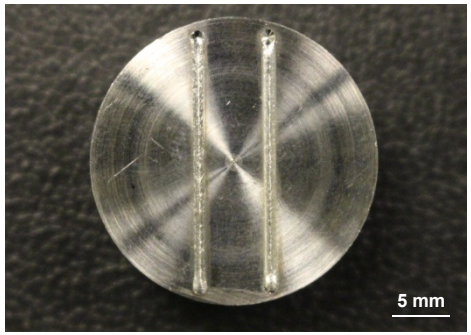
Concentric: CW



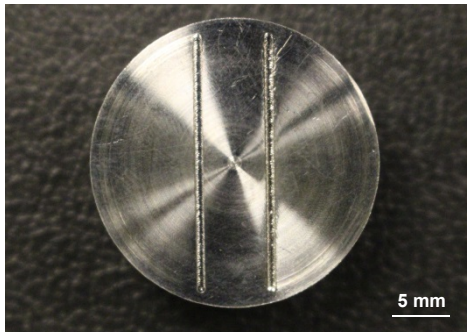
Concentric: Pulsed



Linear: CW

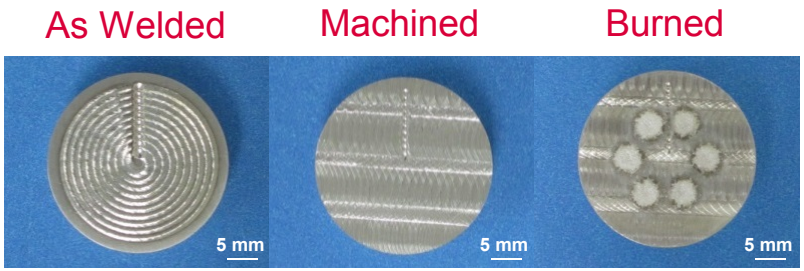


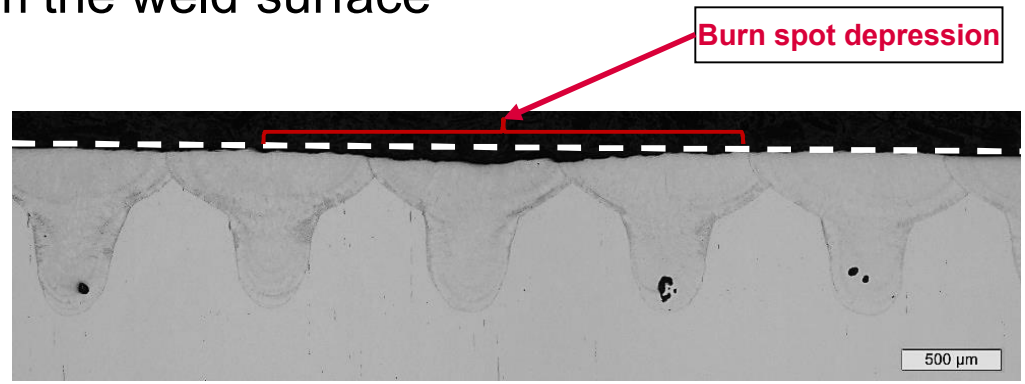
Linear: Pulsed



Characterization Techniques

- **Bulk composition analysis:** Spark OES
  - Concentric weld samples
  - Bulk measurement from the weld surface

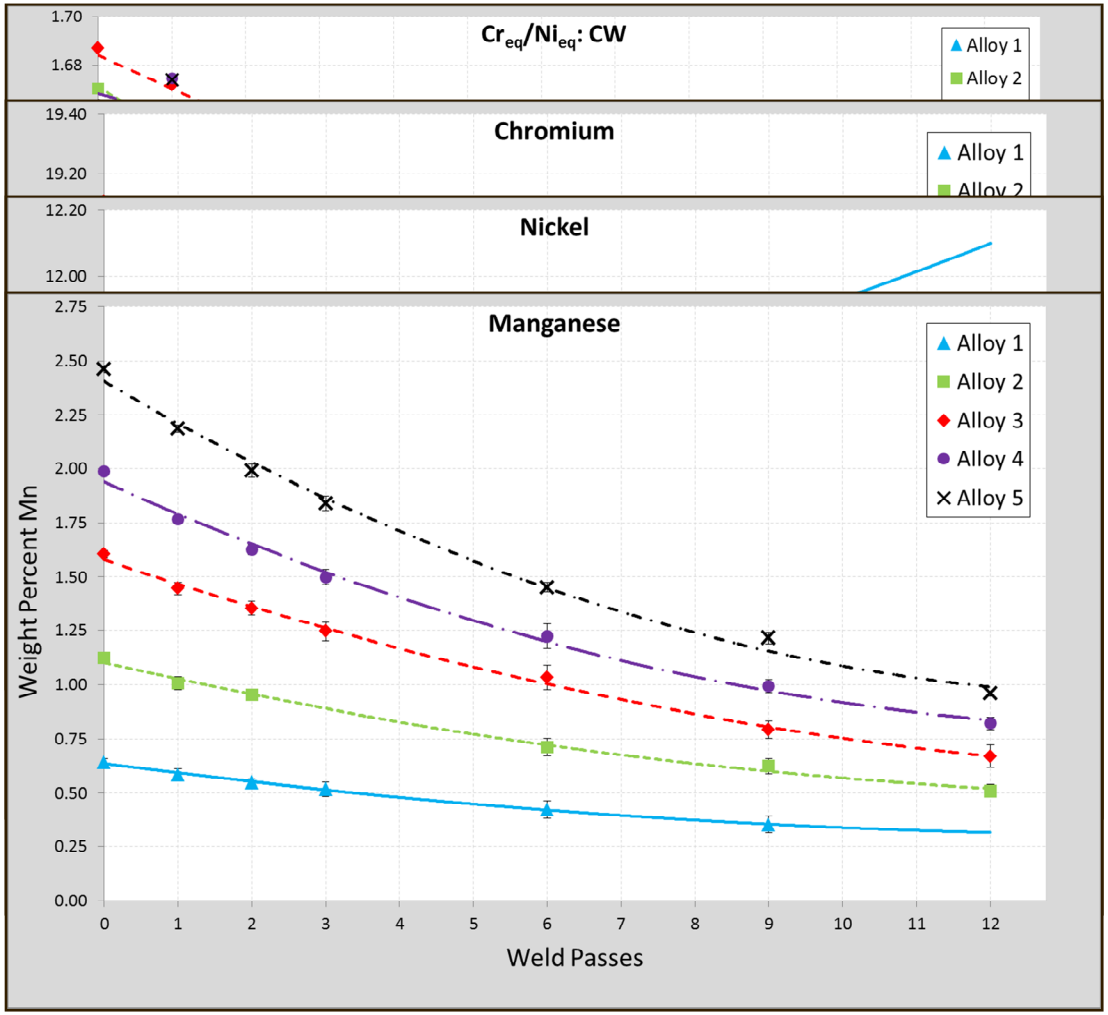




- **Local composition analysis:** EPMA
  - Linear weld samples
  - Measure spatial composition variation in weld pool
  - Determine solidification mode

Continuous Wave Rewelding

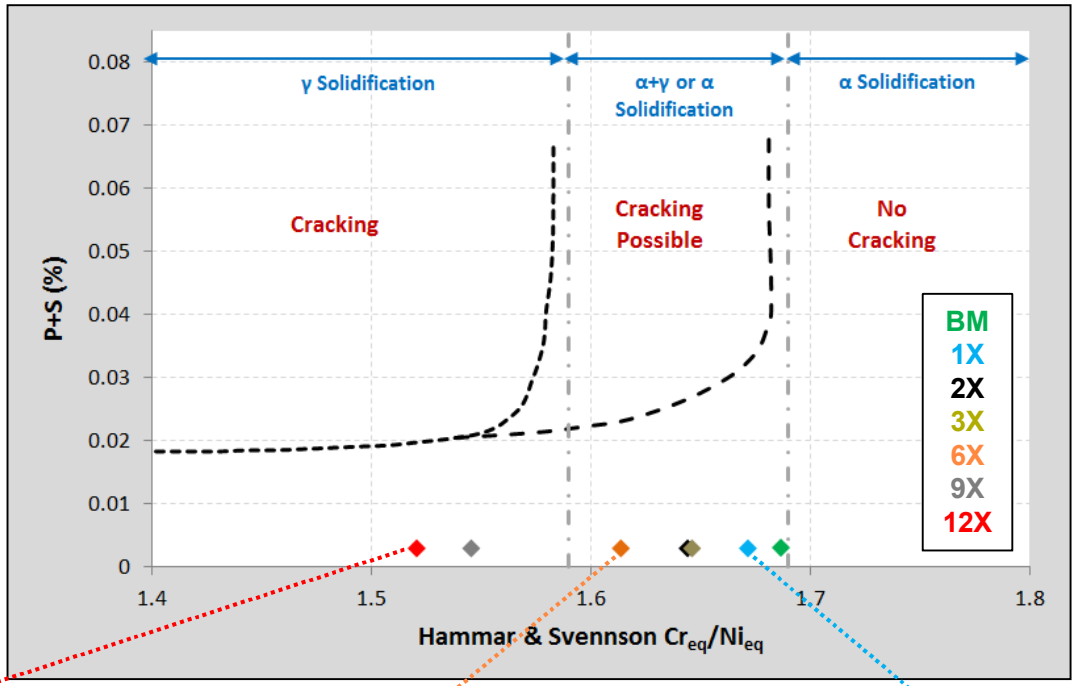
- Monotonic decrease in Cr_{eq}/Ni_{eq}
- Decrease in Cr and Mn
- Increase in Ni
- Vaporization trends not strongly dependent on starting Mn level



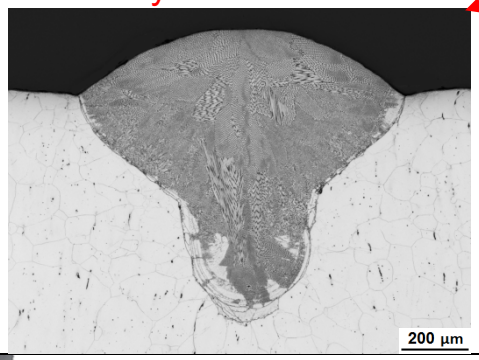
Cr_{eq}/Ni_{eq} Evolution

Adapted From:
Lippold, J. C. & Lienert, T. J.
Sci. Technol. Wel. Joi. **8** (2003) 1-9.

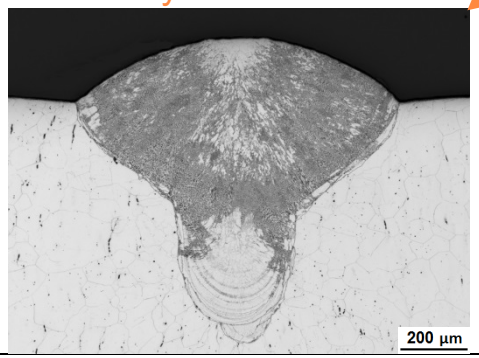
- Weldability diagram for laser welding of austenitic stainless steels
- Good prediction of solidification mode



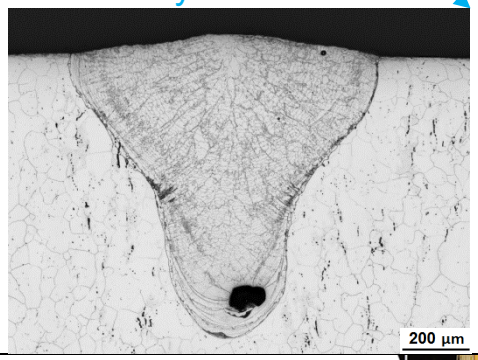
Alloy 3: 12X CW



Alloy 3: 6X CW



Alloy 3: 1X CW

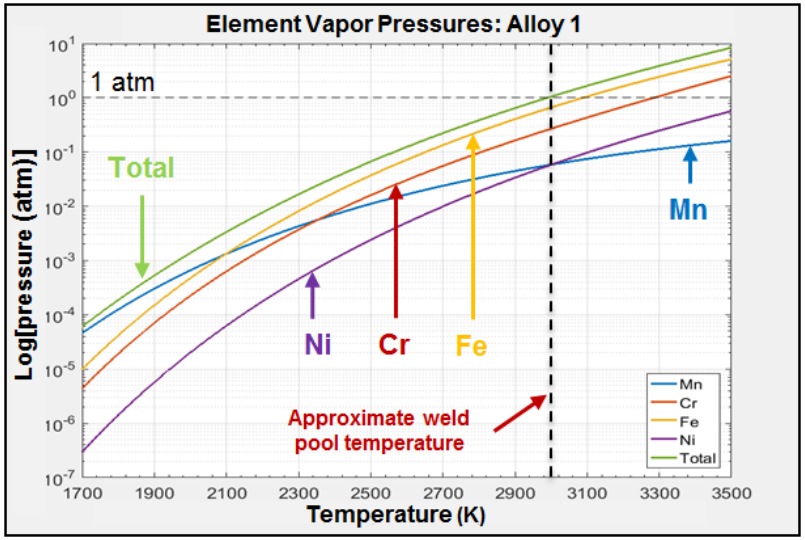


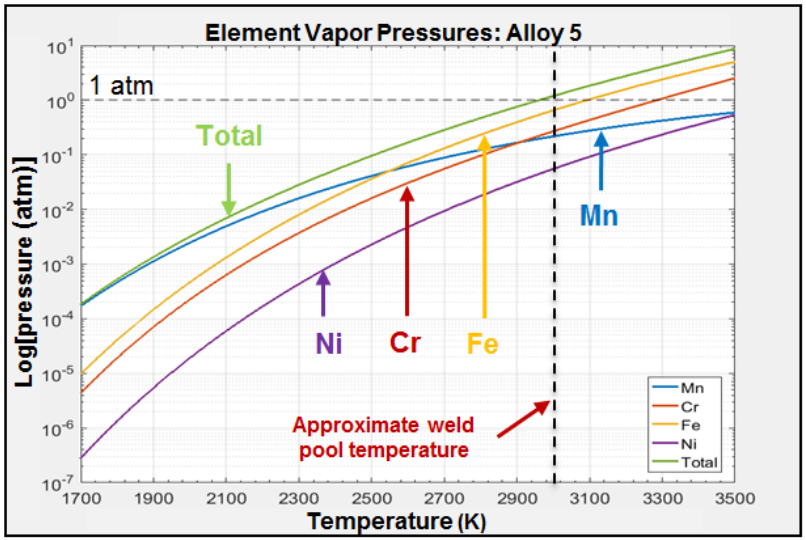
Vapor Pressure

- Manganese has highest equilibrium vapor pressure over pure liquid
- Mole fraction of elements is important
  - Manganese not the main vaporization species

$$P_i = X_i P_i^0$$

P_i – Equilibrium vapor pressure of element i over the alloy
X_i – Mole fraction of element i in the alloy
P_i^0 – Equilibrium vapor pressure of element i over pure liquid

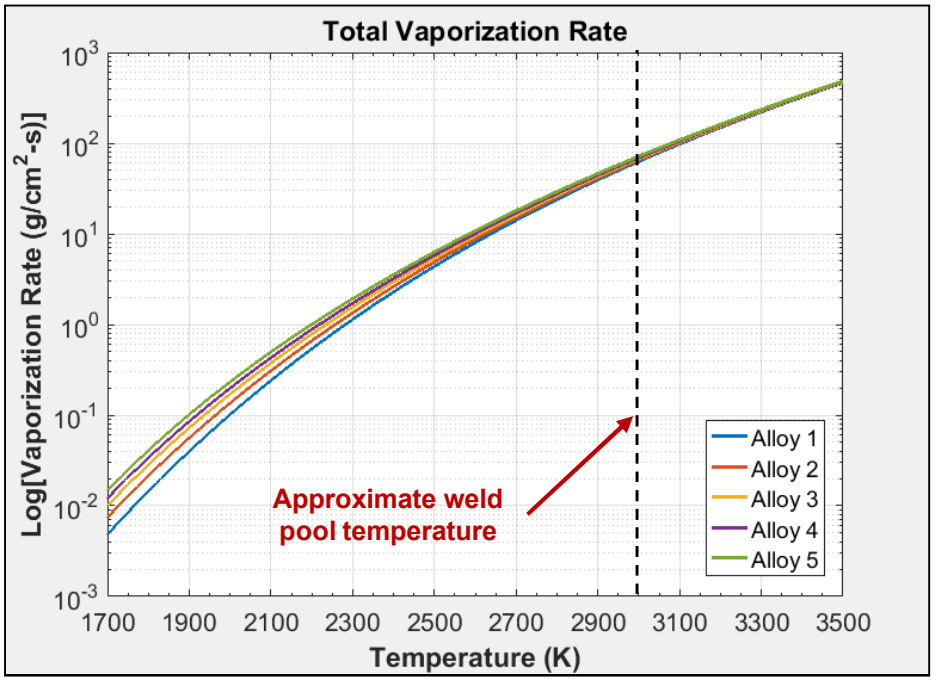




X. He, P.W. Fuerschbach, & T. DebRoy
J. Appl. Phys. **94** (2003) 6949-6958.

Qualitative Vaporization Modeling

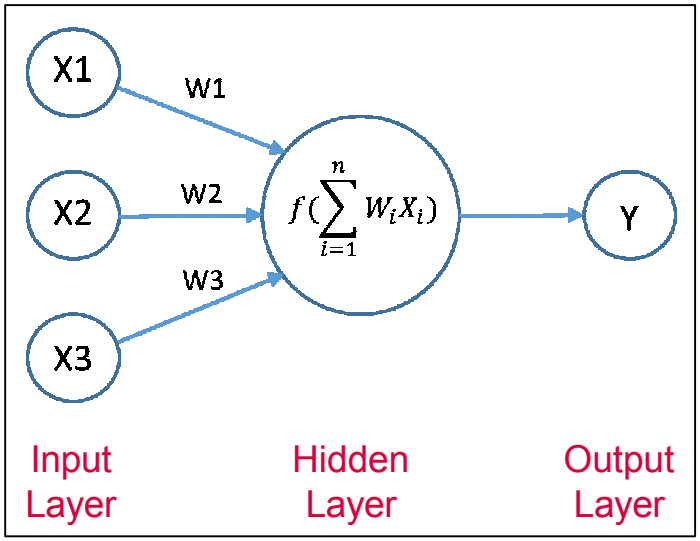
- Langmuir equation used for relative comparison of vaporization rates
  - Vaporization is a function of vapor pressure and temperature
  - Overestimates actual vaporization rate
  - Vaporization rate similar at high weld pool temperatures



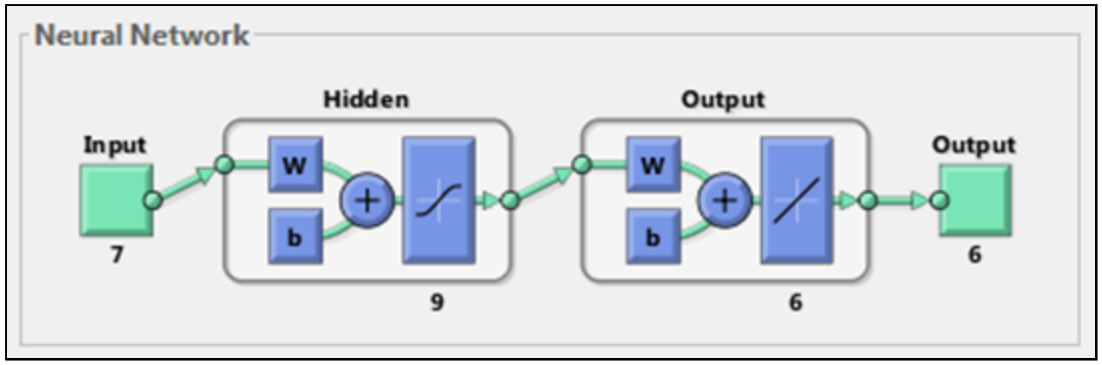
Block-Bolten, A. & Eagar, T.W.
Metall. Trans. B **15B** (1984) 461-469.

Neural Network Modeling

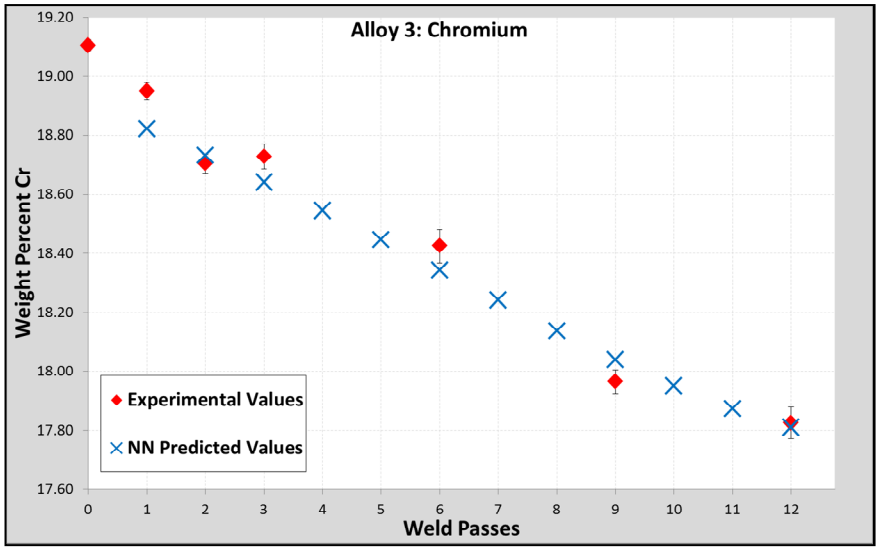
- Neural network developed and trained using CW experimental data
  - MATLAB Neural Network Toolbox
  - Bayesian regularization backpropagation
  - Model in the initial stages

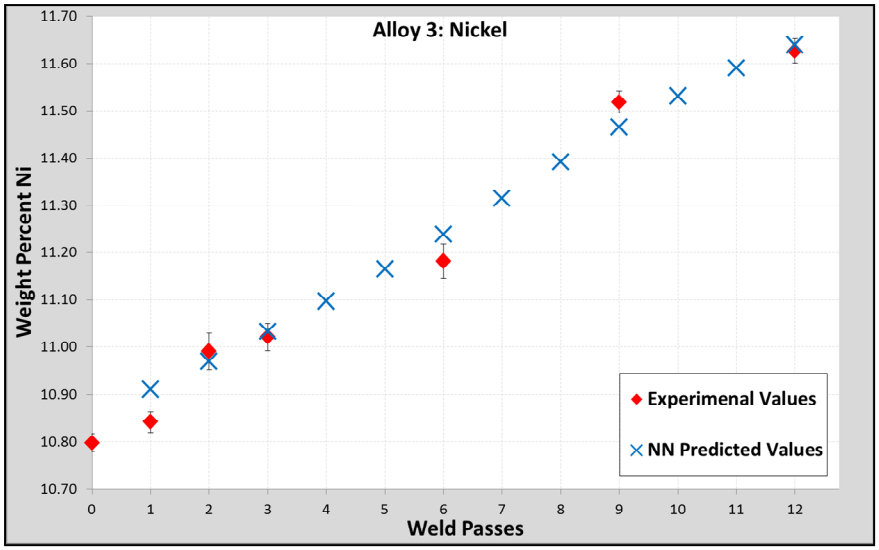


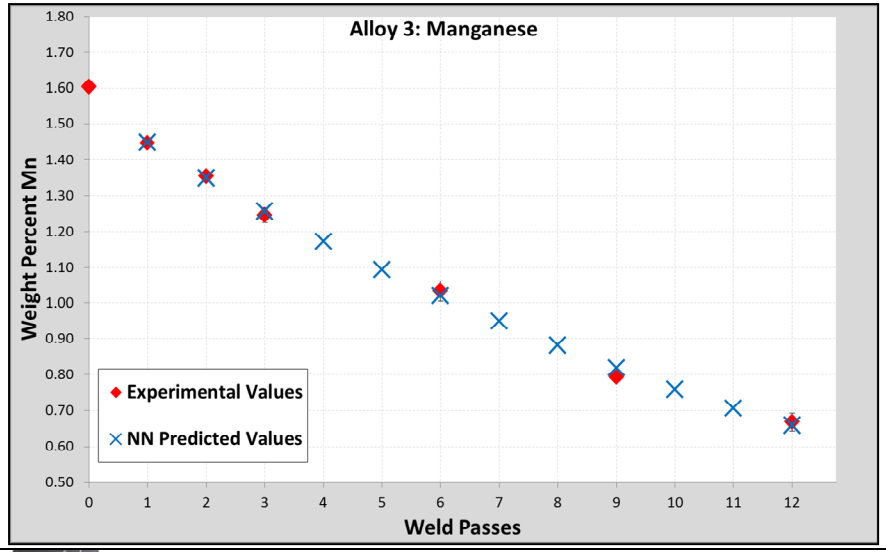
MATLAB Architecture



Neural Network Results





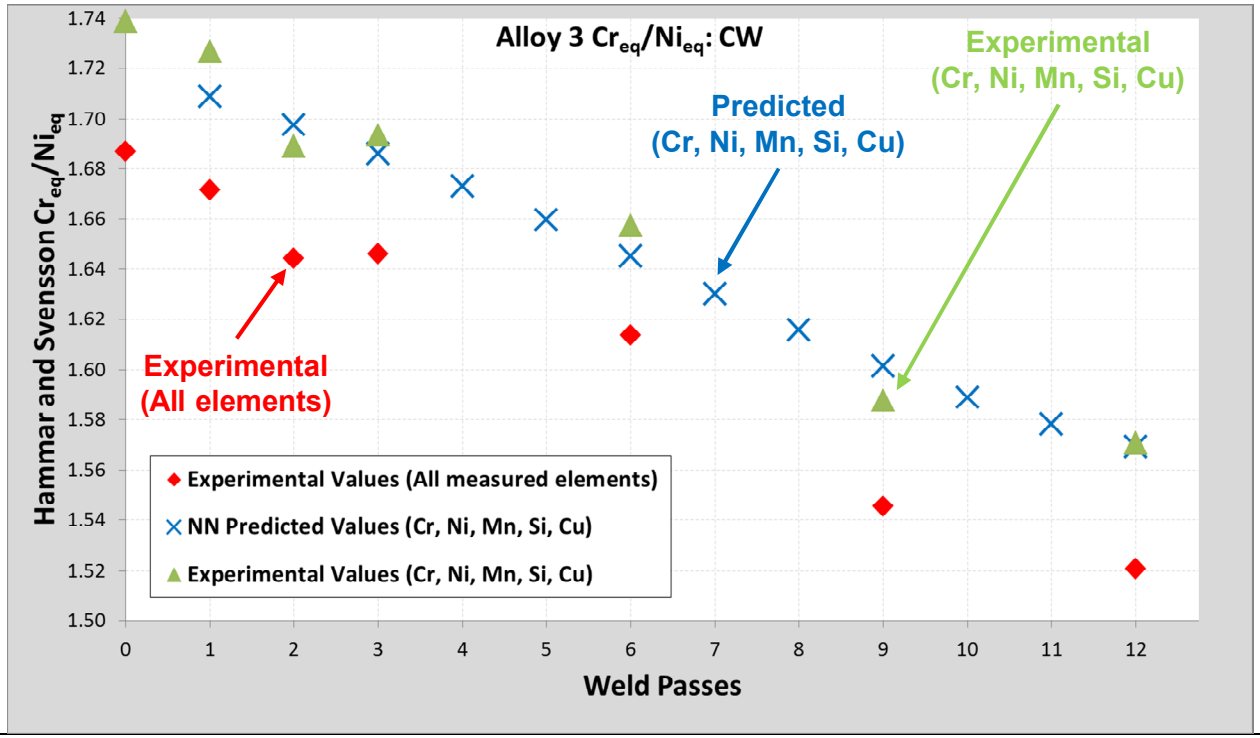


- Prediction matches experimental data well
- Promising engineering tool

Neural Network Results

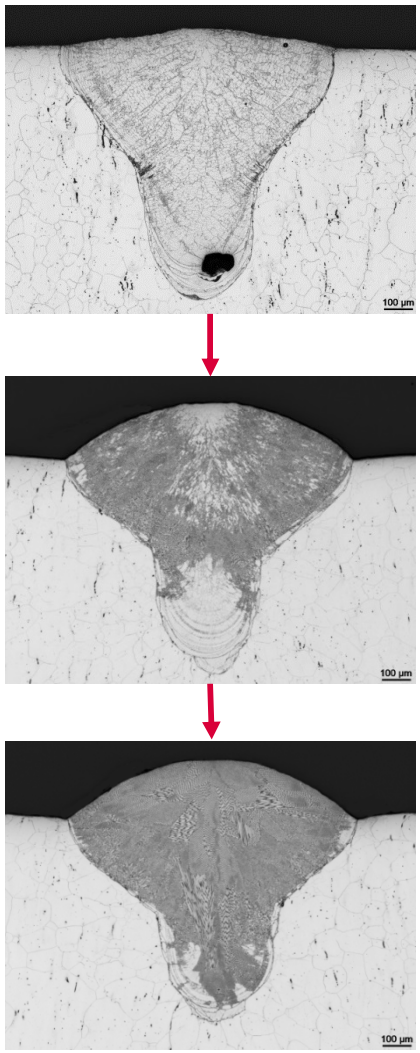
- Input selection is critical
  - Cr_{eq}/Ni_{eq} calculation sensitive to elements considered

Cr_{eq} = Cr+1.37(Mo)+1.5(Si)+2.0(Nb)+3.0(Ti) **Ni_{eq}** = Ni+0.31(Mn)+22(C)+14.2(N)+Cu



Conclusions

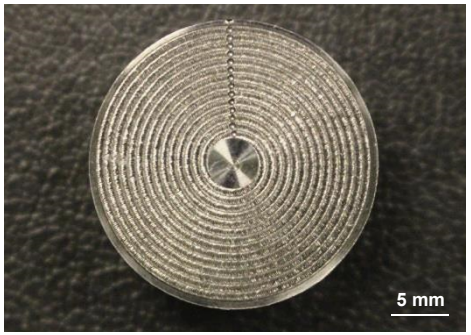
- Vaporization occurs during each reweld pass
  - Monotonic decrease in Cr_{eq}/Ni_{eq}
  - Shift from primary ferrite to primary austenite solidification
- Starting manganese level does not play a significant role in vaporization behavior
- Neural network approach shows promise as an engineering tool



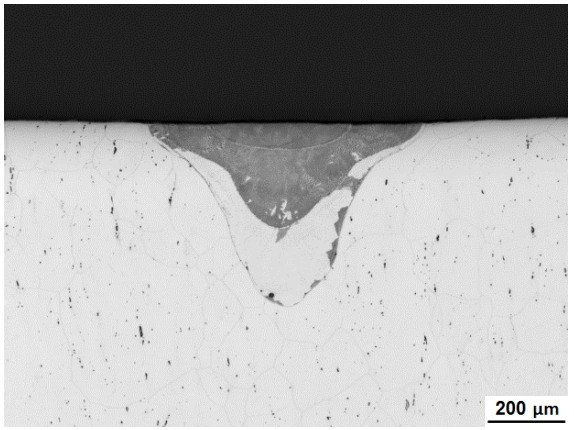
Further Research

- Characterize pulsed weld samples
- Perform EPMA
  - Local composition analysis
  - Understand spatial variation in solidification mode
- Refine neural network using additional experimental data
  - Additional alloys
  - Additional welding parameters
- Develop simple physical model to complement neural network

Pulsed weld sample



2X pulsed weld



Questions?

- **Acknowledgements:**
  - Alex Barr, Matt Vieira, and Mark Reece at Sandia National Laboratories for fabricating weld samples
  - Jeff Rodelas at Sandia National Laboratories, Antonio Ramirez at OSU, and João Oliveira at OSU for providing thoughtful insights and ideas
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