Novel Dissimilar Joints between 2.25Cr-1Mo Steel and Alloy 800H through Additive Manufacturing

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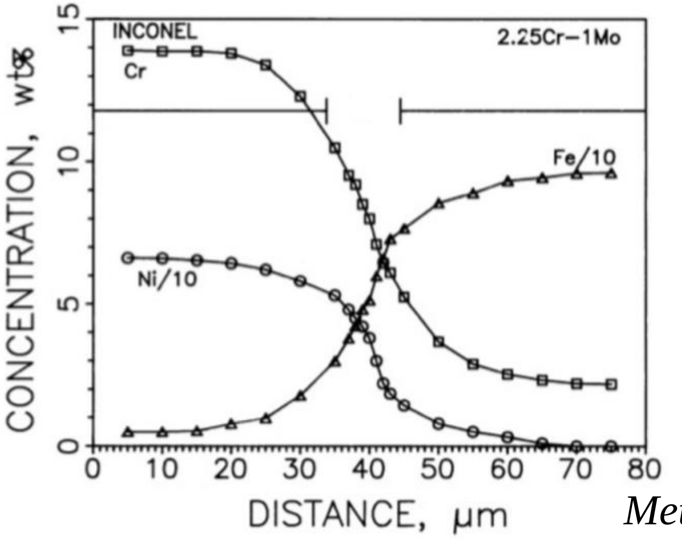
Advisor: S. A. David, Oak Ridge National Laboratory
TPOC: Dr. S. Sham, U.S. Department of Energy

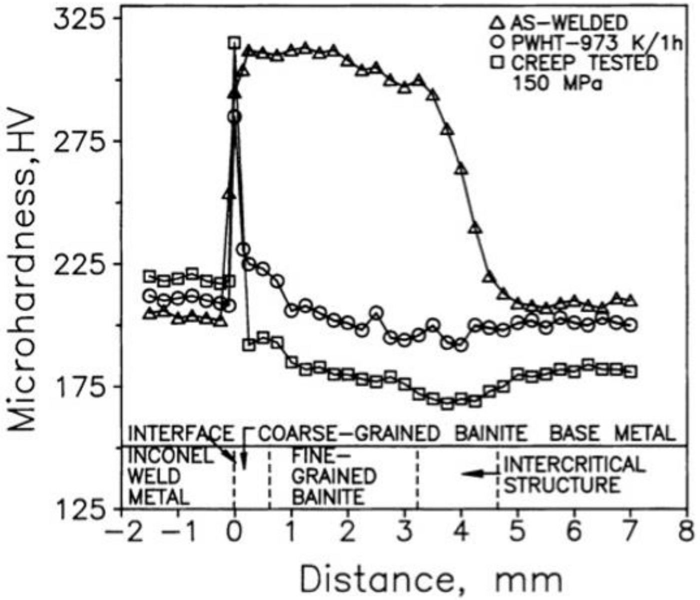
Dissimilar metal welds in power plants

Ferritic (2.25Cr-1Mo Steel) to austenitic (800H) joints

Sharp changes in composition and micro-hardness

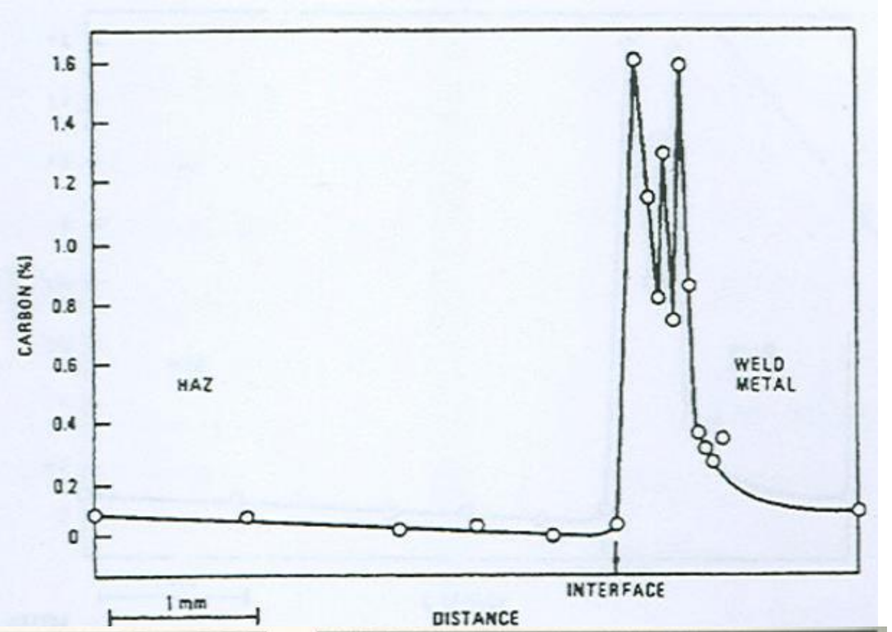


Laha
Metall. Mater. Trans A
2001



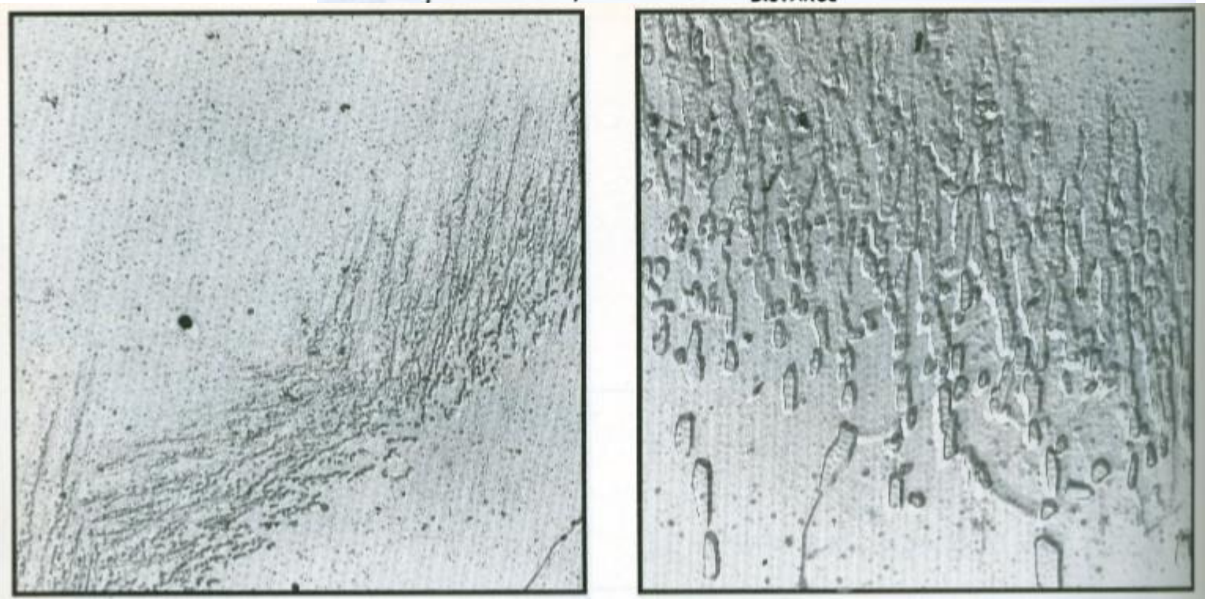
Carbon diffusion towards austentic alloy

Ryder
Trends in Electric Utility Research, 1984



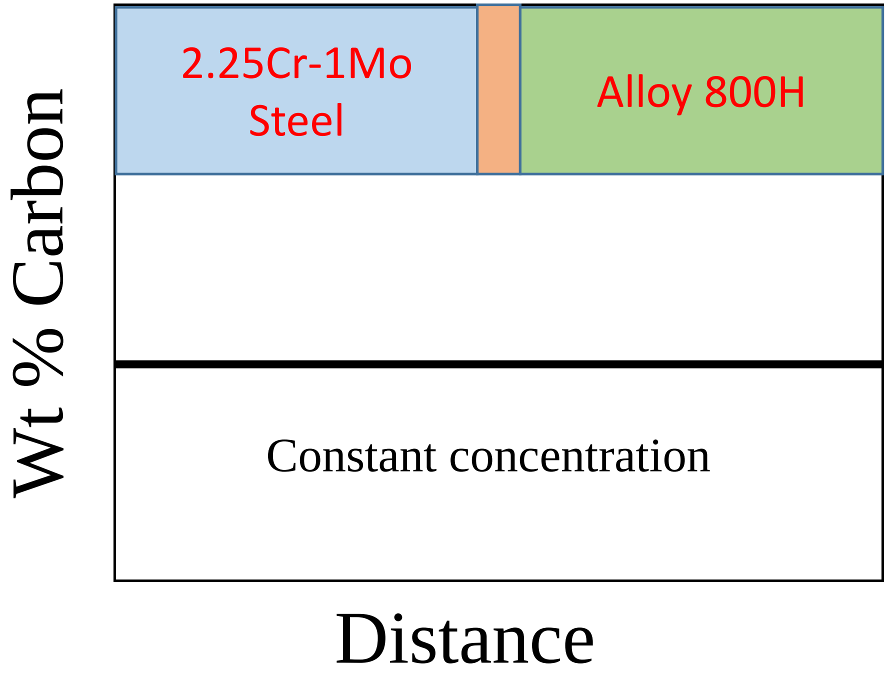
Carbide formation along HAZ of ferritic steel

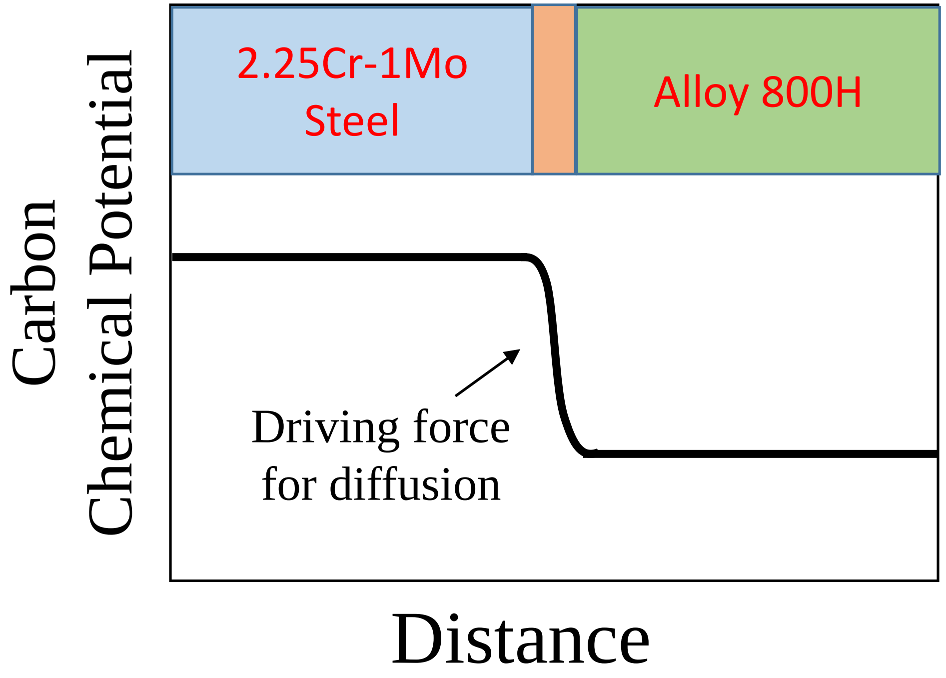
Gittos
Welding Journal
1992



What causes carbon diffusion?
Carbon chemical potential gradient

- Diffusion flux is typically governed by the concentration gradient in many applications
- Here, the system needs to be define in terms of the chemical potential gradient





Fick's first law of diffusion

$$J_i = -D_i \frac{dc_i}{dx} \quad \Rightarrow \quad J_i = -\frac{L_i}{T}\frac{d\mu_i}{dx}$$

Depends on alloying elements (μ_i)

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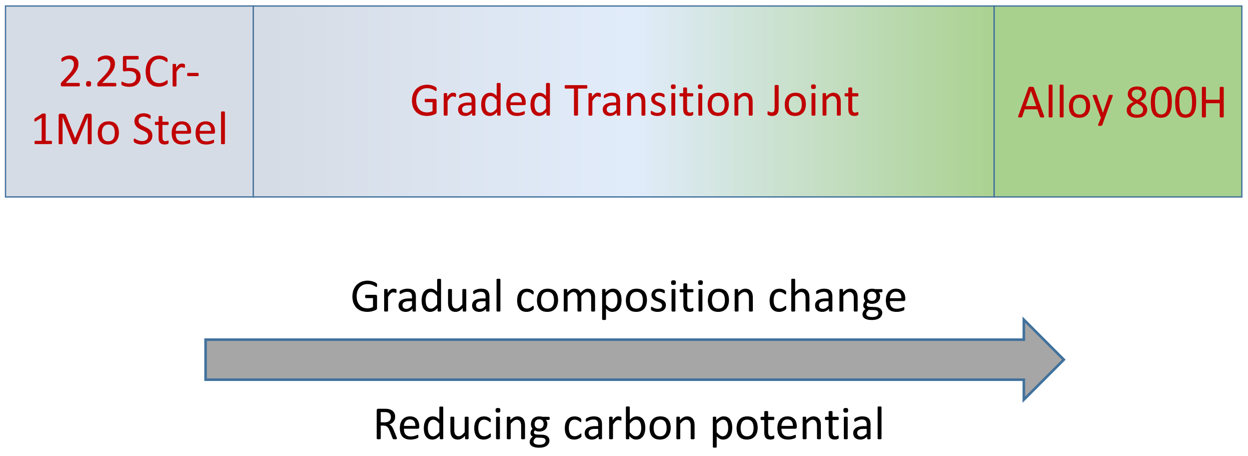
Reduce carbon diffusion by minimizing carbon potential gradient

(a) Thermodynamically model carbon potential gradient for various compositionally graded transition joints

(b) Fabricate selected transition joints by additive manufacturing

(c) Test fabricated joints

2.25Cr-1Mo Steel	
Element	Wt%
C	0.1
Cr	2.25
Fe	Balance
Mo	1
Mn	0.5
Ni	0.045
Si	0.5



Alloy 800H	
Element	Wt%
Al	0.6
C	0.1
Cr	21
Cu	0.75
Fe	39.5
Mn	1.5
Ni	Balance
Si	1
Ti	0.6

Eliminates abrupt changes in mechanical properties, microstructure, and composition

Reduces carbon potential gradient

How is chemical composition optimized?

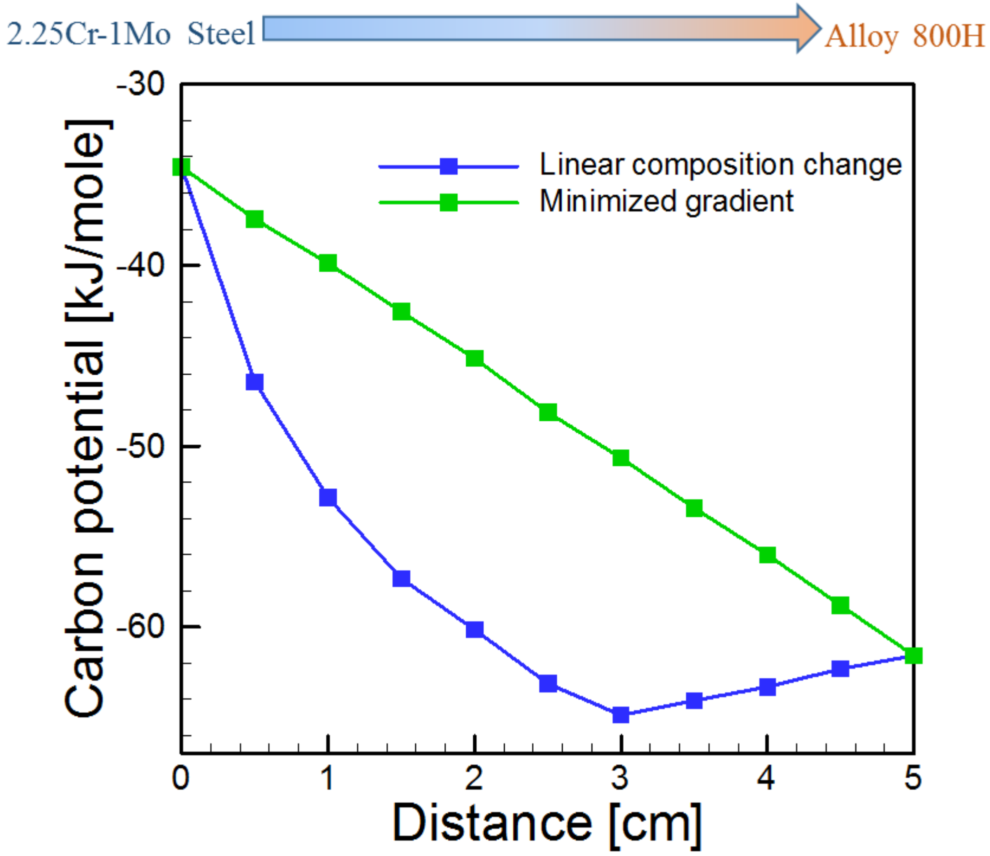
1. Plot C-potential for a linear composition change and compare to minimized C-potential gradient

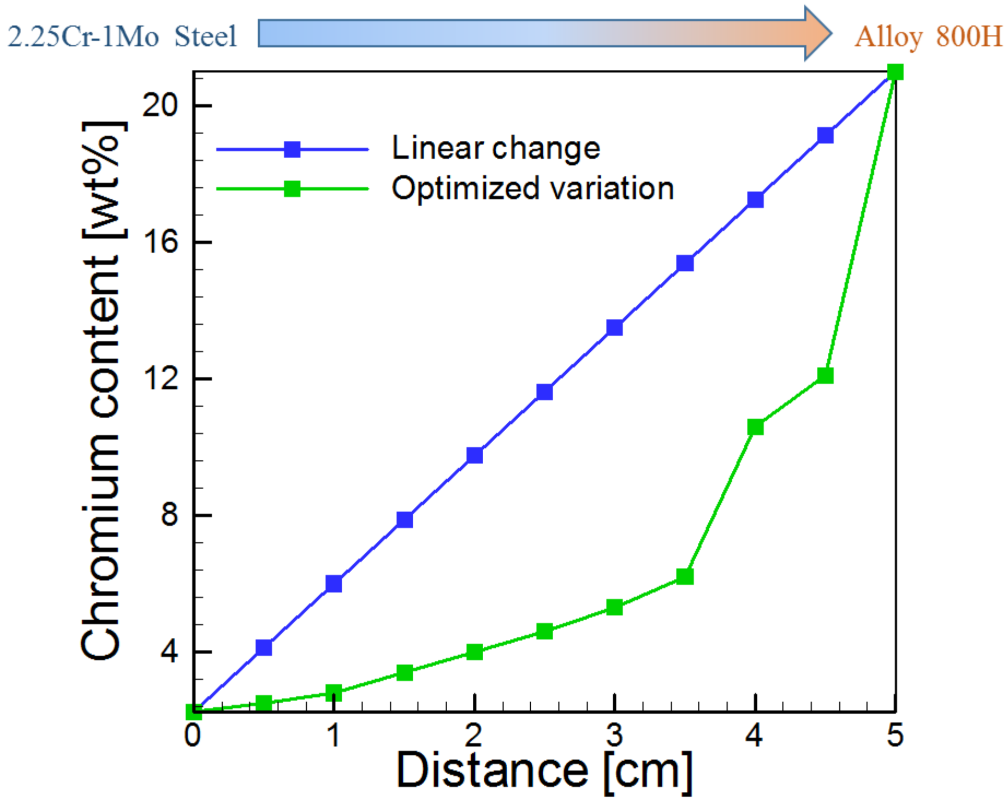
2. Calculate C-potential as a function of Cr concentration at all locations along transition joint

3. Use search algorithm for Cr concentration that gives target C-potential value

4. Repeat steps 1-3 for all locations. Output Cr concentration profile

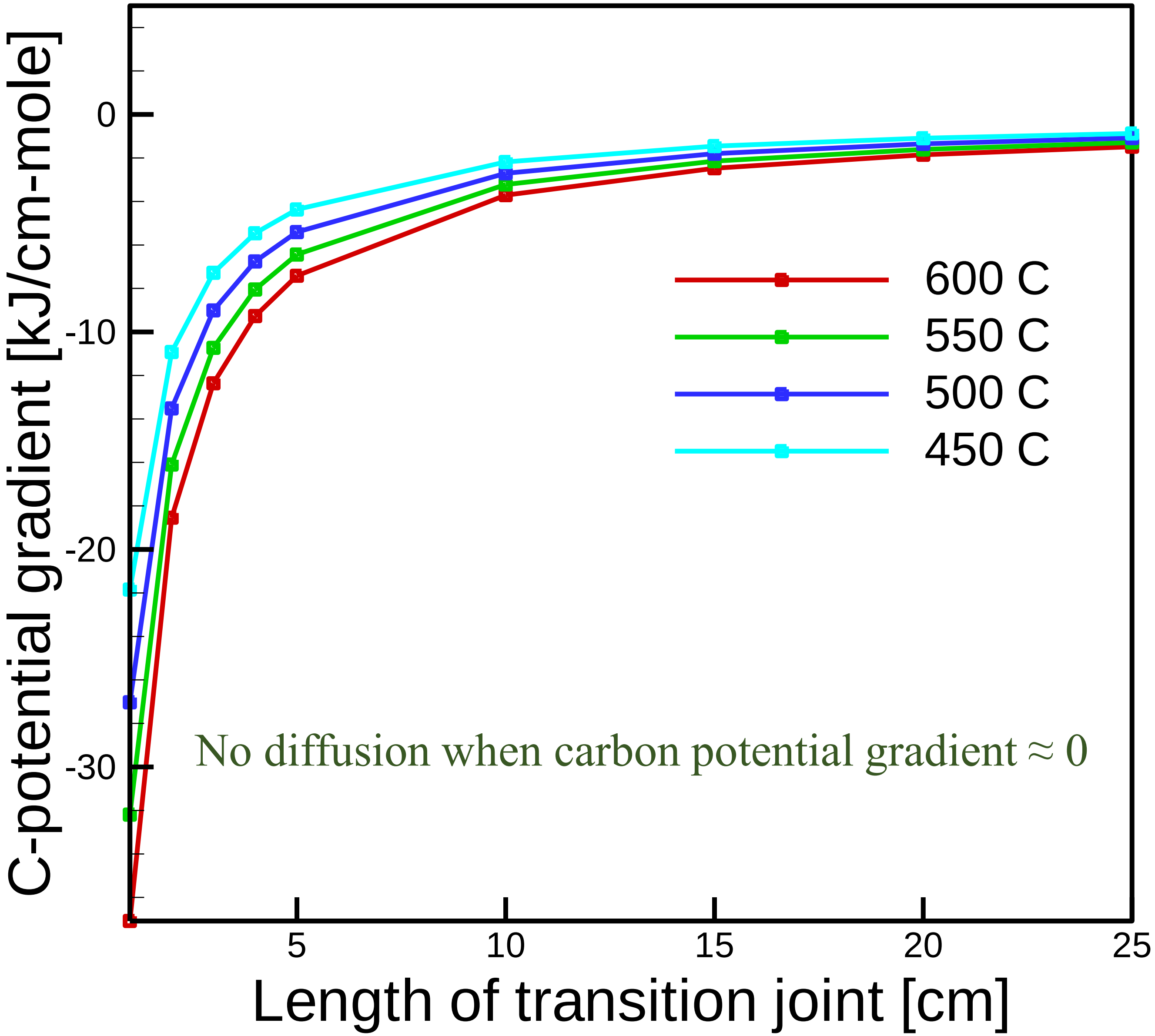
5. Build transition joint with minimized C-potential gradient





How long should the transition joint be?

2.25Cr-1Mo Steel → Alloy 800H



Carbon potential gradient = Driving force for carbon diffusion

At constant T, driving force depends on length

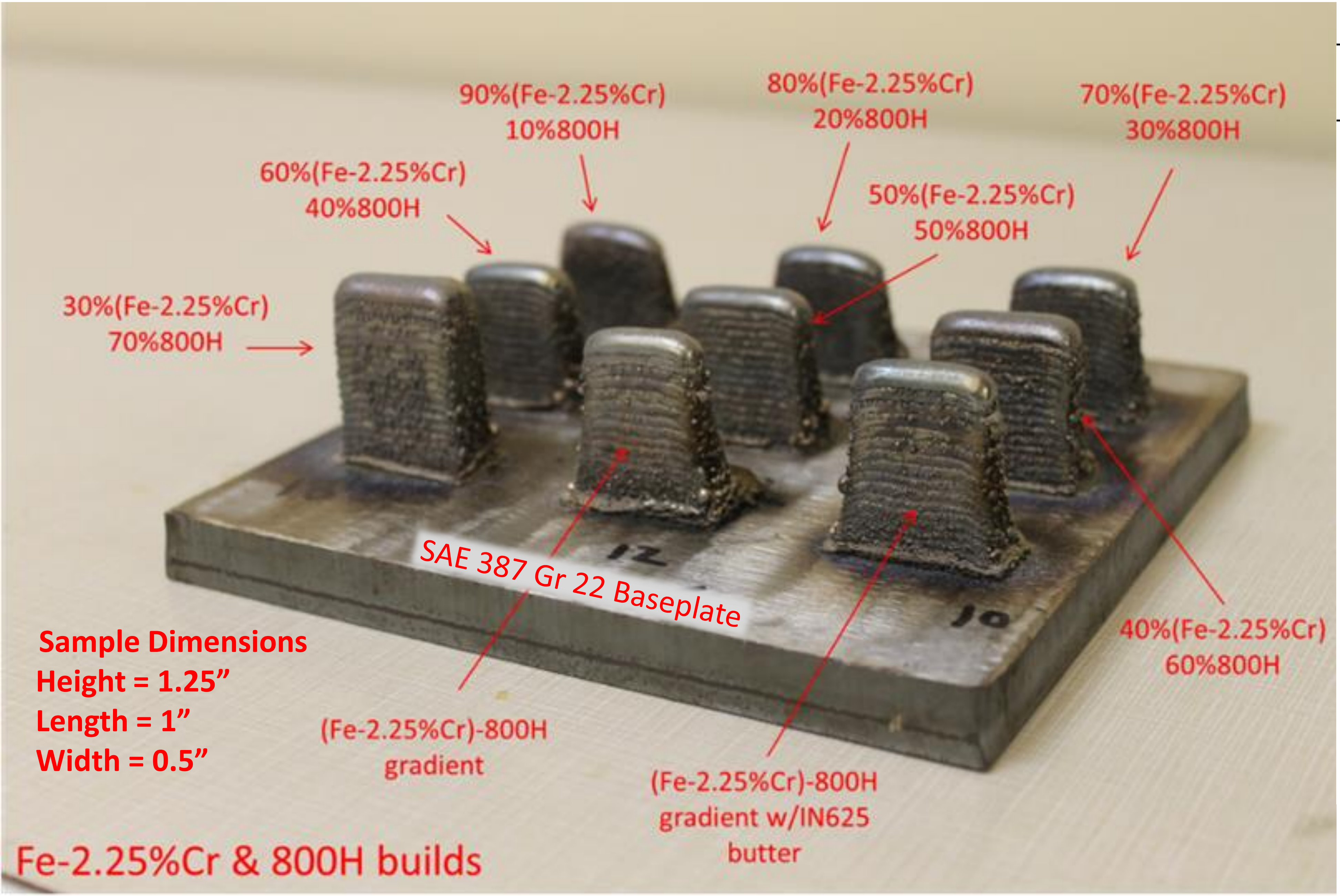
Assume an optimized change in C-potential from beginning to end of joint

Plot: Dependence of carbon potential gradient on length of transition joint for 4 temperatures

Finding:

- Marginal benefits for joints over 5 cm

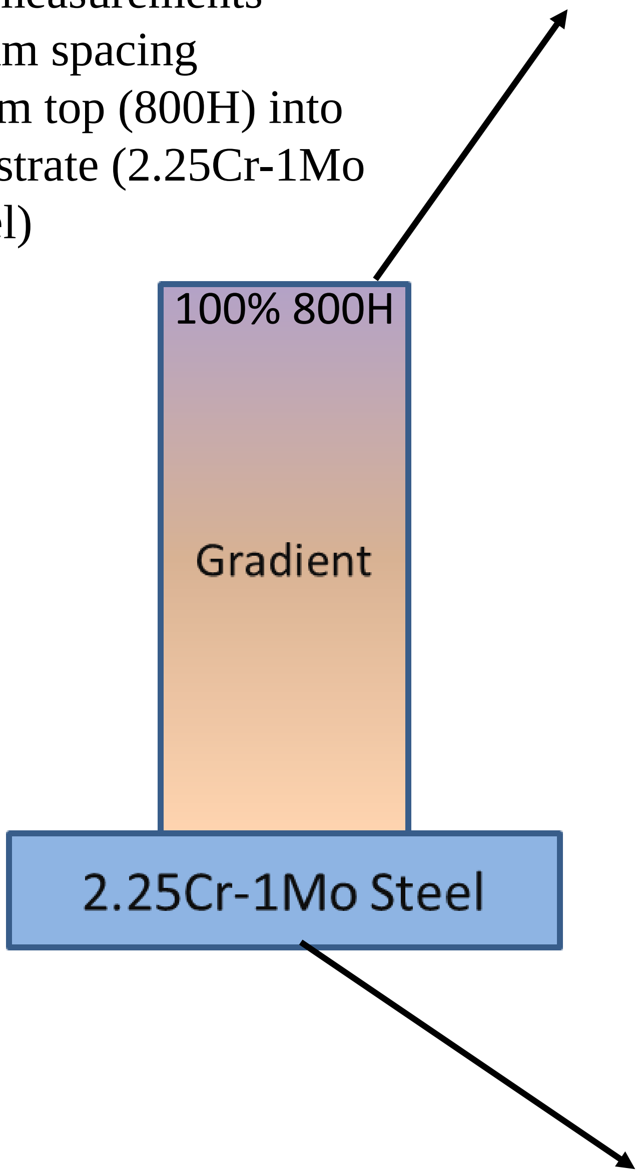
Fabrication of compositionally graded test specimens



Parameters	Values
Laser power (W)	2000
Beam radius (mm)	2.0
Scanning speed (mm/s)	10.6
Layer thickness (mm)	0.89
Substrate thickness (mm)	12.5

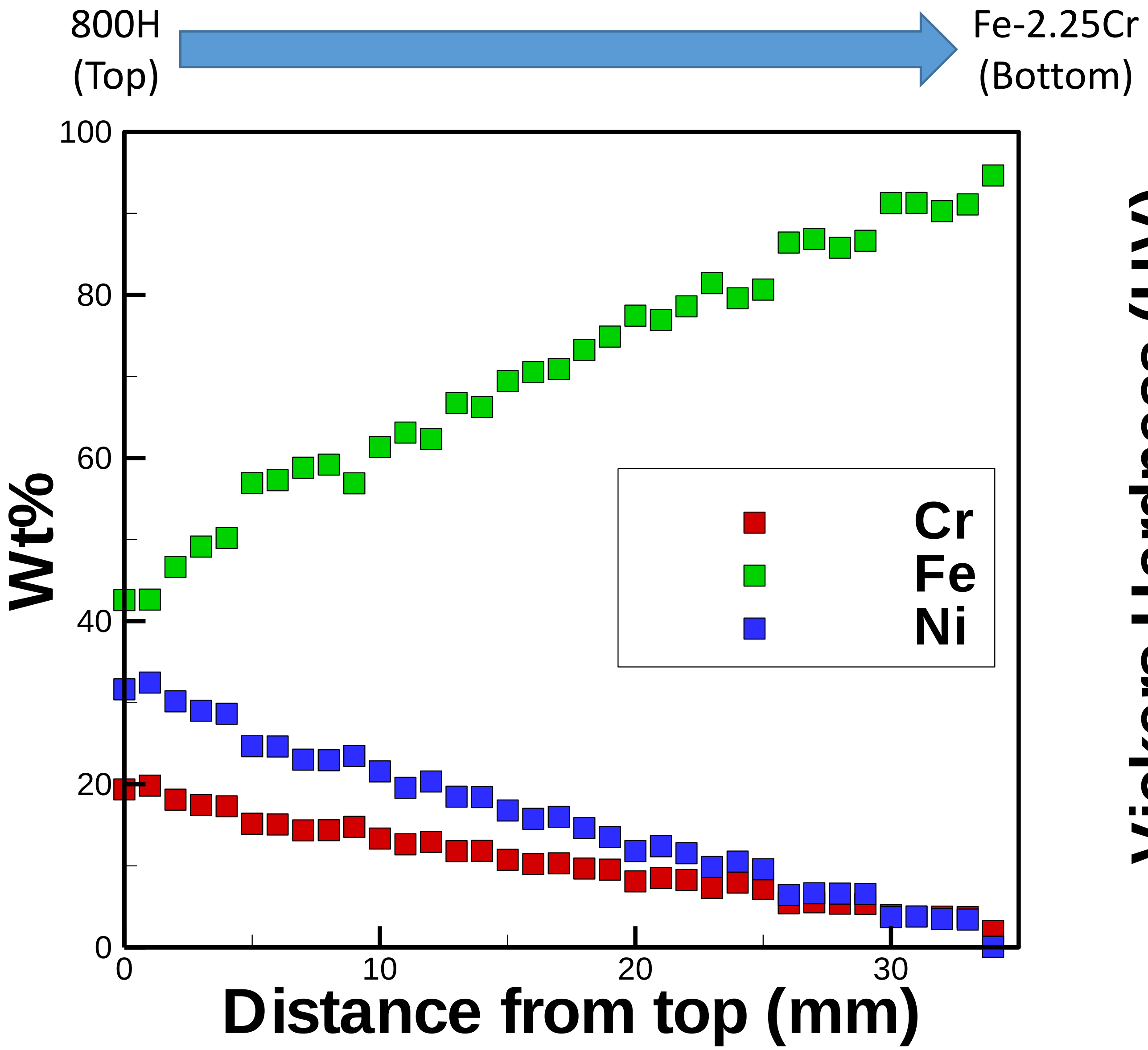
EPMA Results

- 35 measurements
- 1 mm spacing
- From top (800H) into substrate (2.25Cr-1Mo steel)

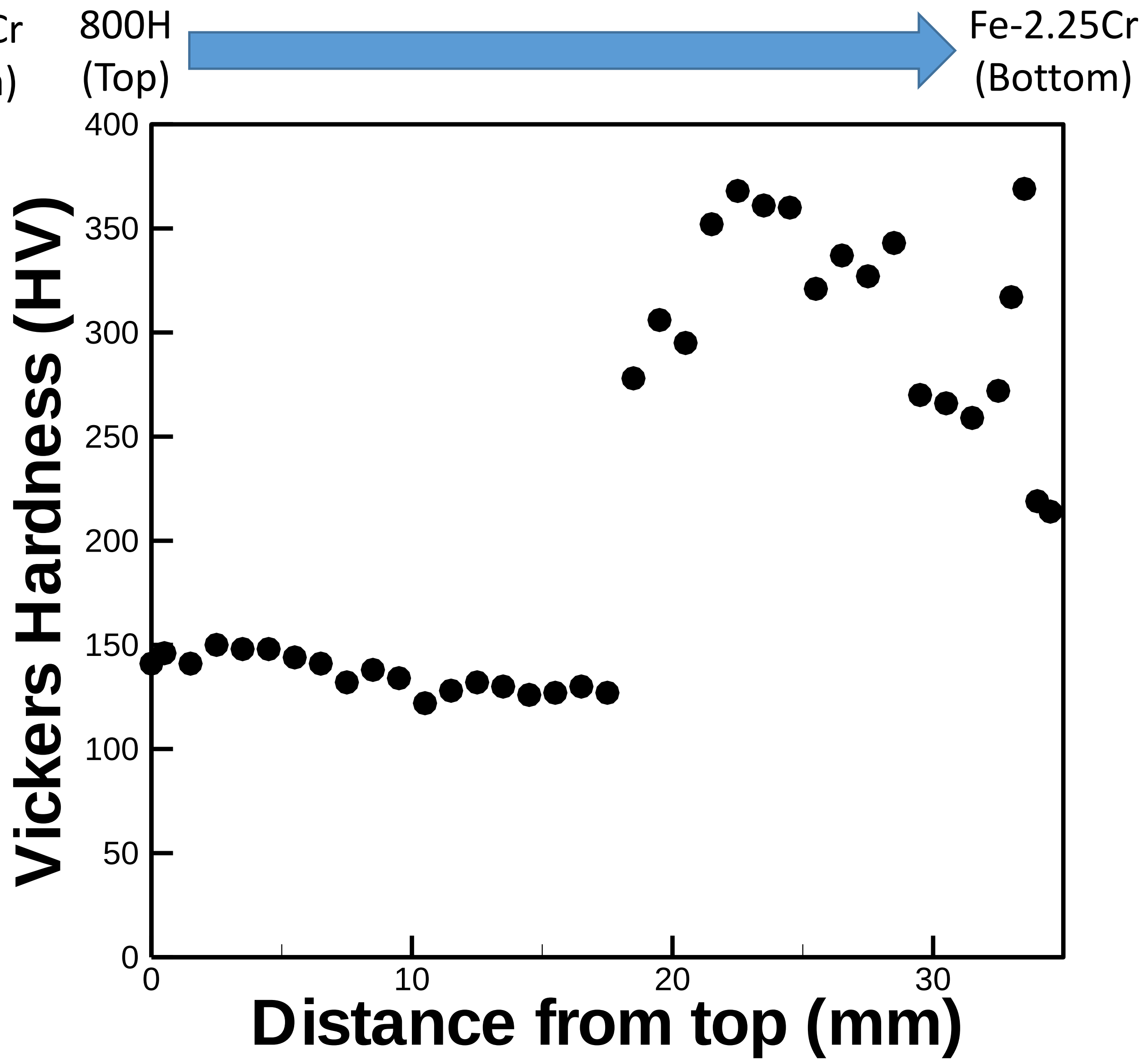


Dist. from top [mm]	wt% C	wt% Si	wt% Cr	wt% Fe	wt% Mo	wt% Mn	wt% Ni	wt% Al
0	1.359	0.572	19.363	42.577	-	4.038	31.636	0.48
1	-	0.631	19.824	42.647	0.01	4.321	32.461	0.40
2	0.568	0.488	18.106	46.655	0.022	3.667	30.161	0.333
3	0.457	0.405	17.459	49.153	0.008	3.193	29.018	0.306
4	-	0.452	17.293	50.185	-	3.608	28.645	0.309
5	-	0.34	15.161	56.919	0.009	2.823	24.656	0.259
6	-	0.328	15.068	57.277	-	2.74	24.636	0.248
7	0.507	0.31	14.343	58.807	0.017	2.767	23.02	0.229
8	0.135	0.359	14.37	59.196	0.004	2.76	22.94	0.236
9	0.703	0.455	14.78	56.895	0.016	3.433	23.469	0.251
10	0.666	0.303	13.348	61.34	0.051	2.521	21.574	0.198
11	1.252	0.389	12.634	63.119	0.014	2.832	19.574	0.186
	…	…	…	…	…	…	…	…
26	0.429	0.099	5.408	86.416	0.045	1.12	6.435	0.047
27	-	0.127	5.515	86.867	0.047	1.212	6.629	0.020
28	0.905	0.113	5.358	85.776	0.022	1.167	6.589	0.068
29	0.115	0.123	5.313	86.643	0.063	1.148	6.542	0.054
30	0.114	0.074	3.967	91.259	0.025	0.842	3.701	0.018
31	0.256	0.08	3.783	91.277	0.008	0.813	3.778	0.005
32	1.498	0.057	3.763	90.27	0.039	0.867	3.488	0.018
33	0.58	0.095	3.717	91.093	0.161	0.922	3.417	0.015
34	-	0.184	1.979	94.64	1.43	1.89	0.081	0.034

EPMA and Vickers Hardness Measurements

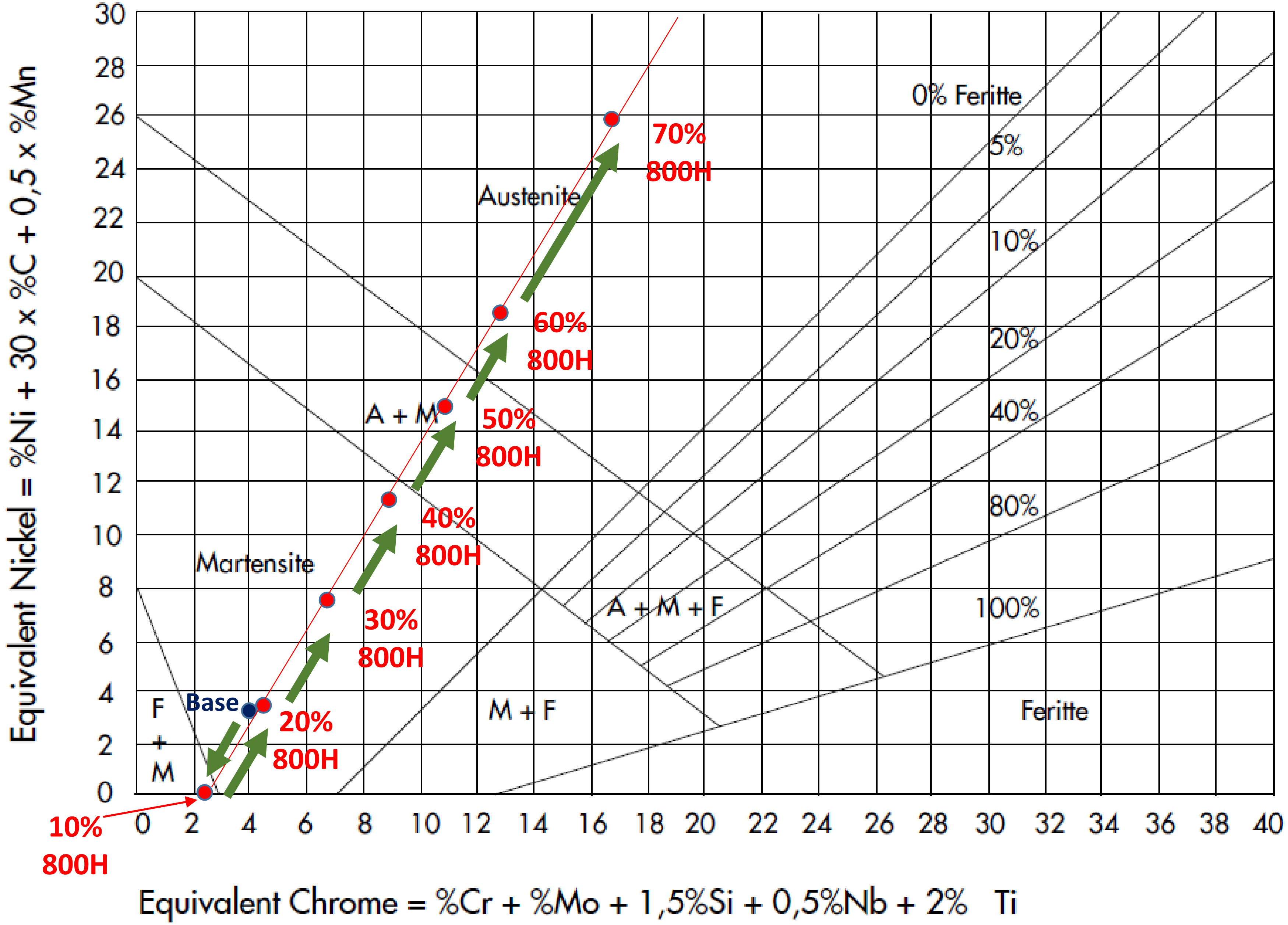


EPMA done at PSU MCL on CAMECA SXFive



Hardness measurements taken on LECO M-400-G1 at PSU ARL (300g load)

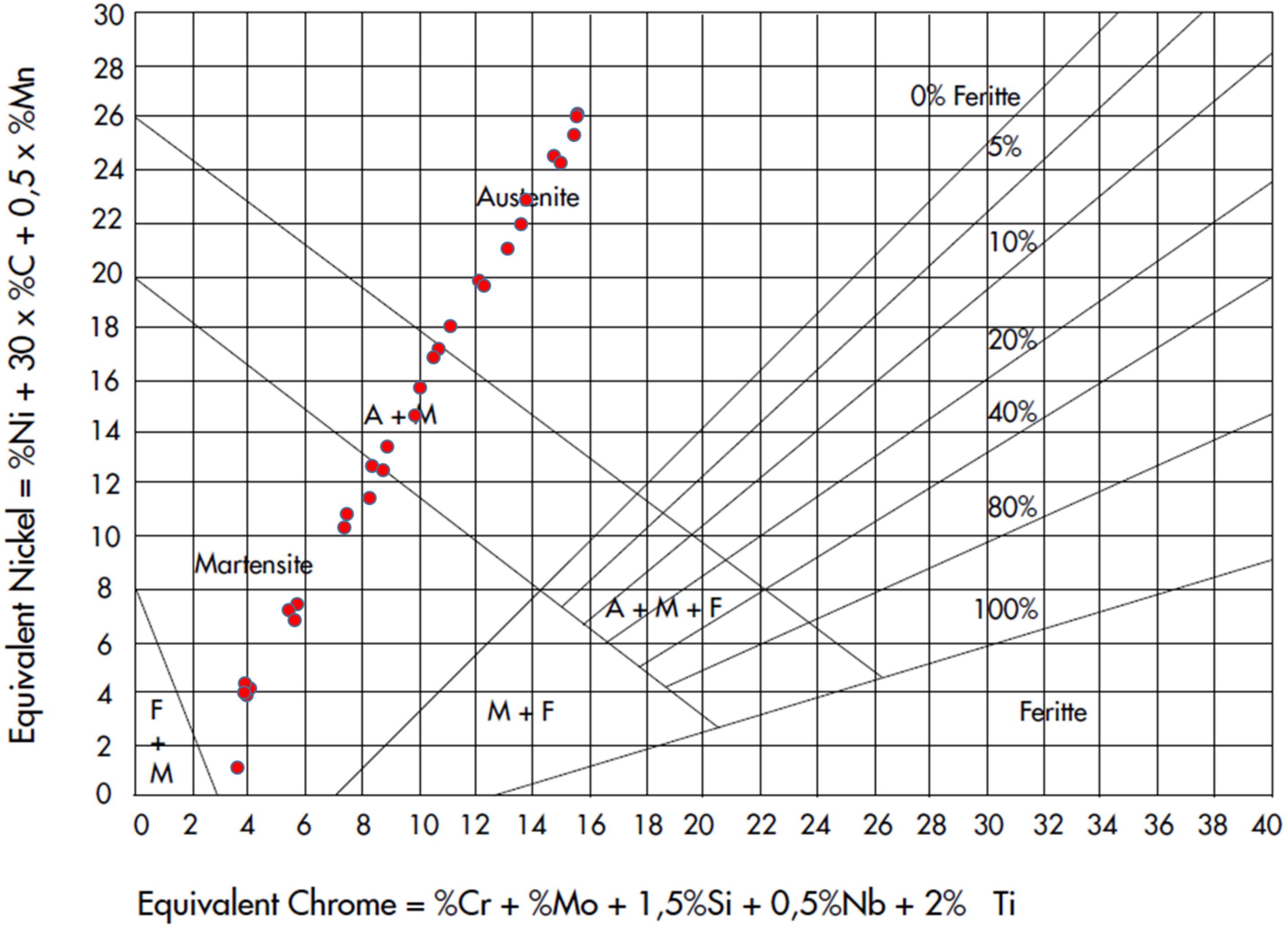
Guide for Microstructure Prediction

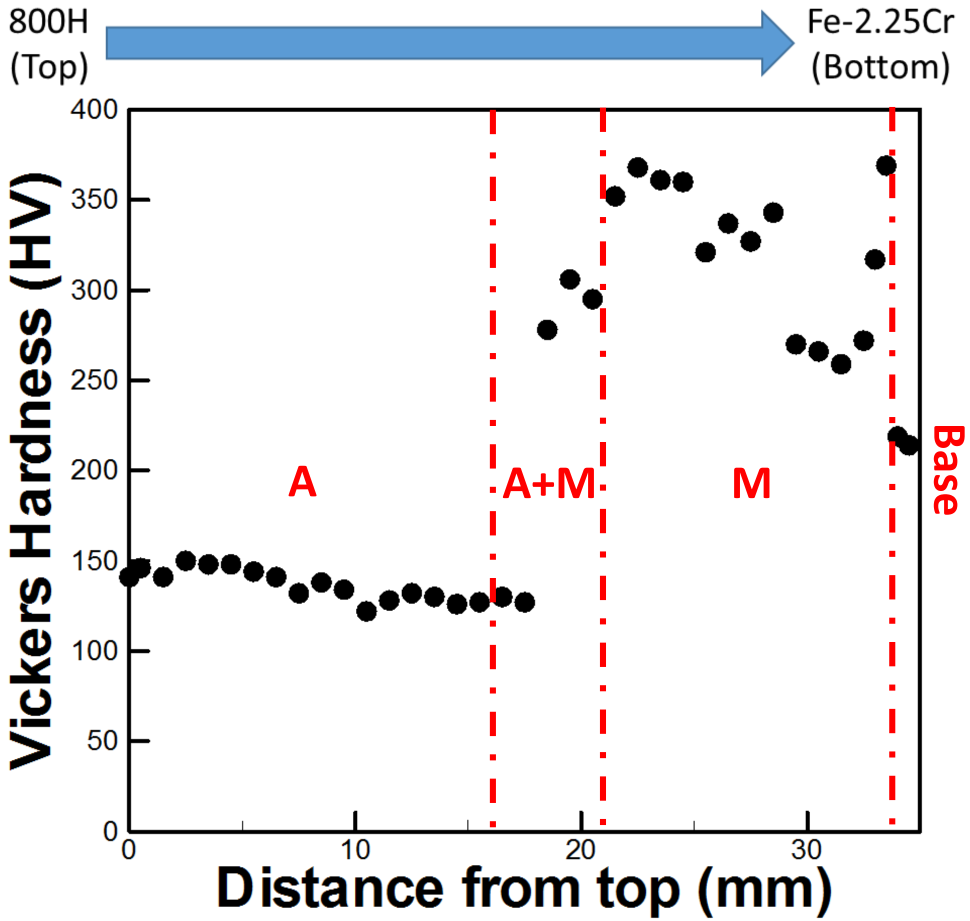


Schaeffler Constitution Diagram

- Commonly used when welding low alloy steels, austenitic stainless steels and dissimilar alloys
- Relates the composition to microstructure based on common cooling rates found in welding
- Here, it is used as a guide for predicting the microstructure in a low alloy steel to austenitic graded alloy

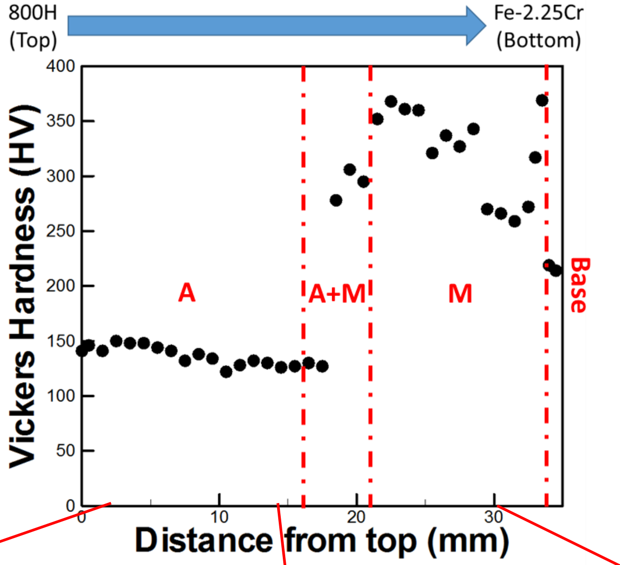
Changes in composition correspond to changes in microstructure

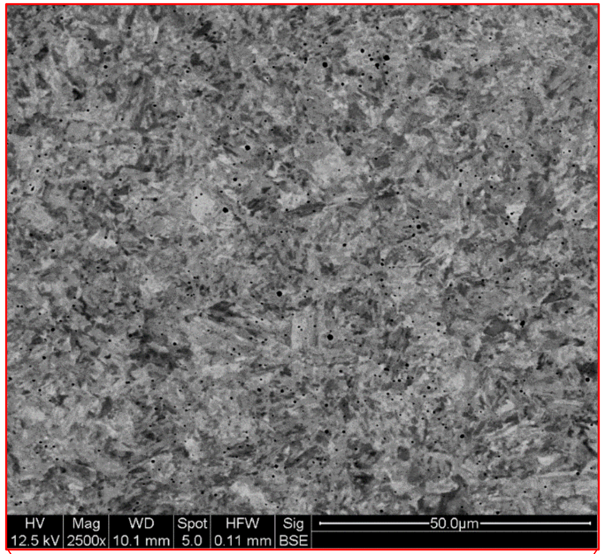




SEM Images

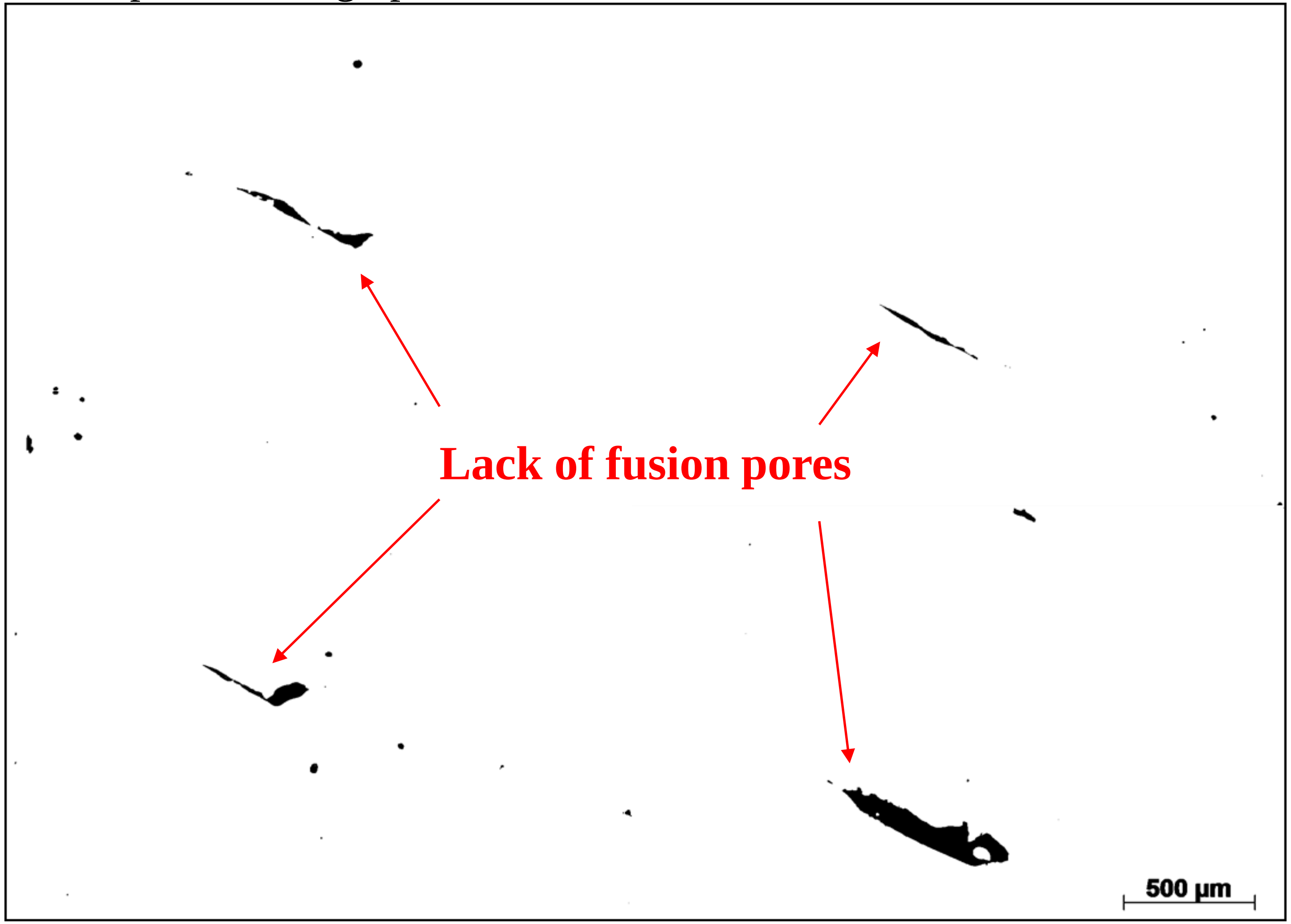
Noticeable change from very fine microstructural constituents to long, elongated columnar grains





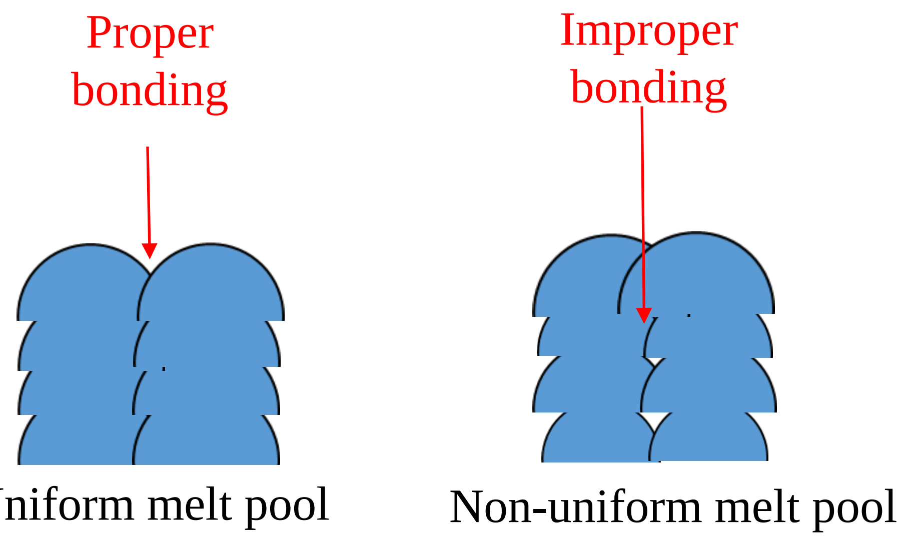
Lack of fusion pores during fabrication

Optical micrograph shown in black and white scale for contrast



- Vertically aligned lack of fusion porosity caused by improper choice of hatch spacing
- Only observed in layers close to baseplate

→ Differences in melt pool dimensions

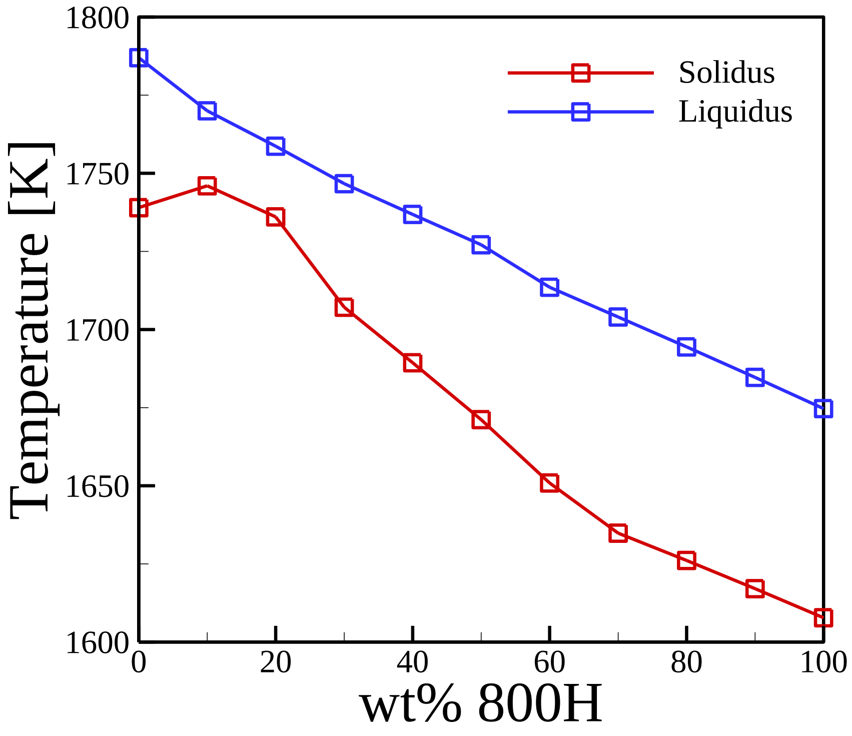


Printability of alloys

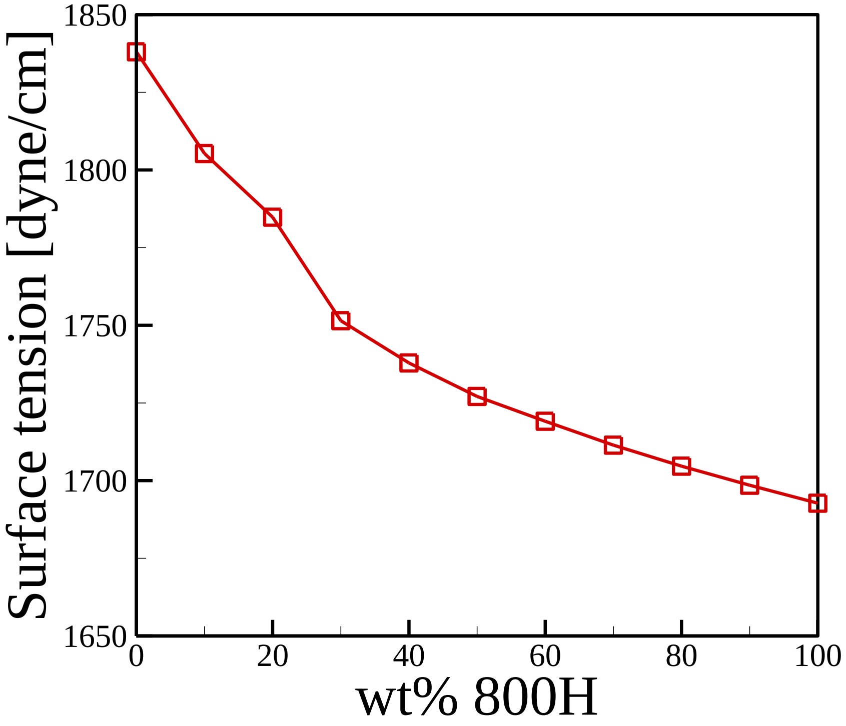
- Not all alloys are printed similarly due to differences in thermo-physical properties
- Leads to differences in molten pool geometry and susceptibility to defects

Notable differences in properties between 2.25Cr-1Mo Steel and Alloy 800H

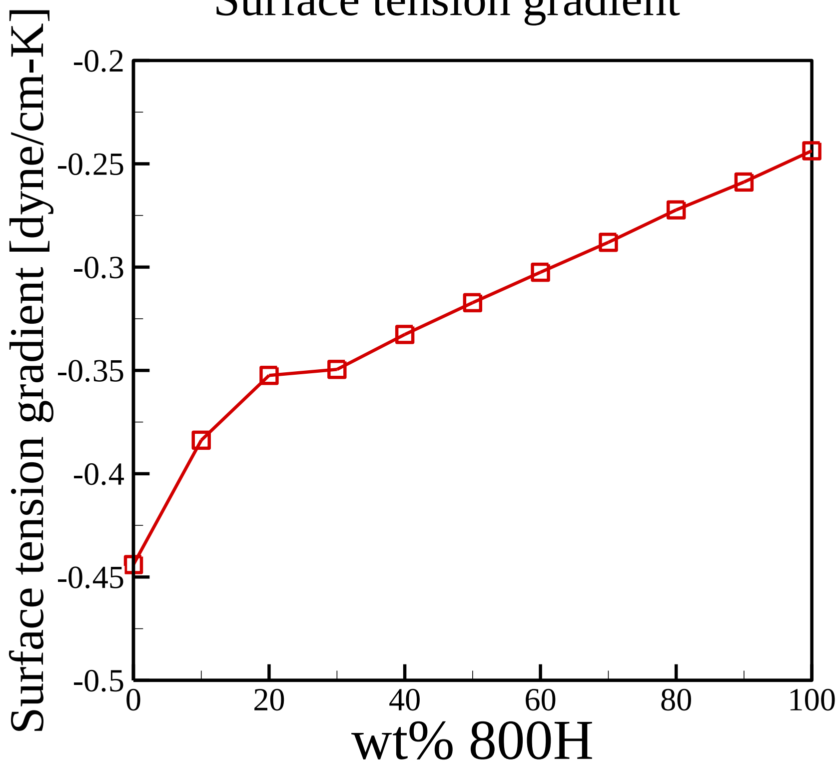
Solidus/Liquidus Temperature



Surface tension at liquidus temperature



Surface tension gradient

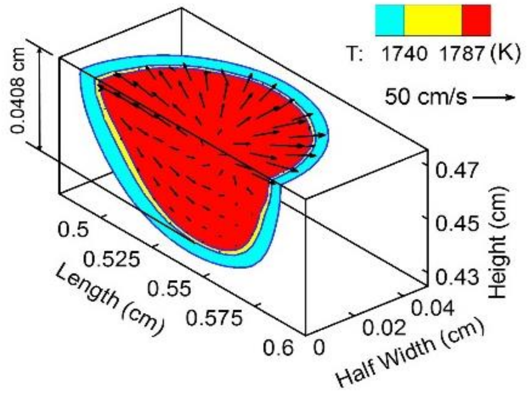


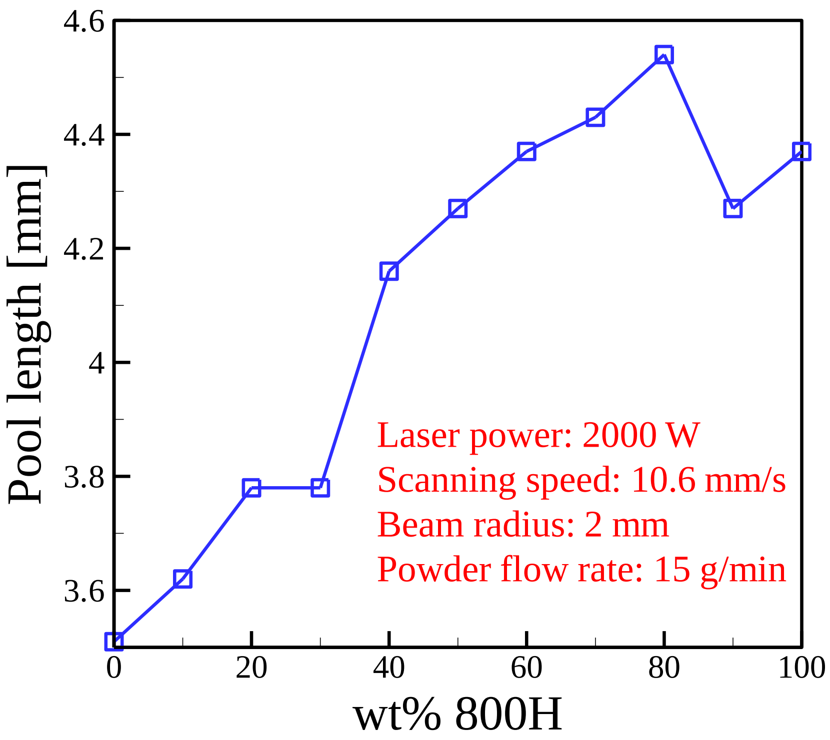
Mukherjee, Zuback, De & DebRoy. Printability of alloys for additive manufacturing. *Scientific Reports*. 2016.

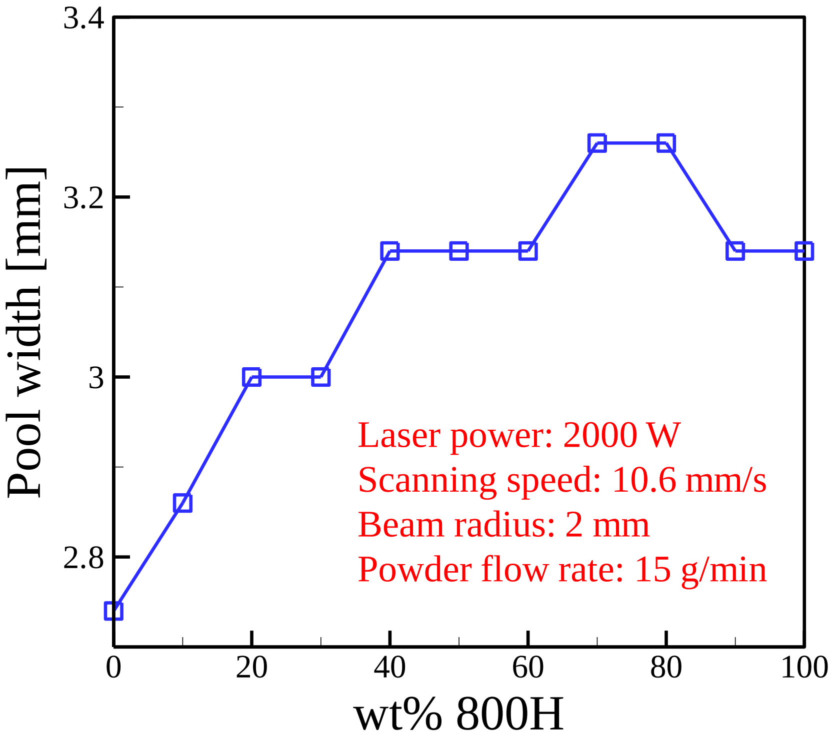
Heat Transfer and Fluid Flow Simulations

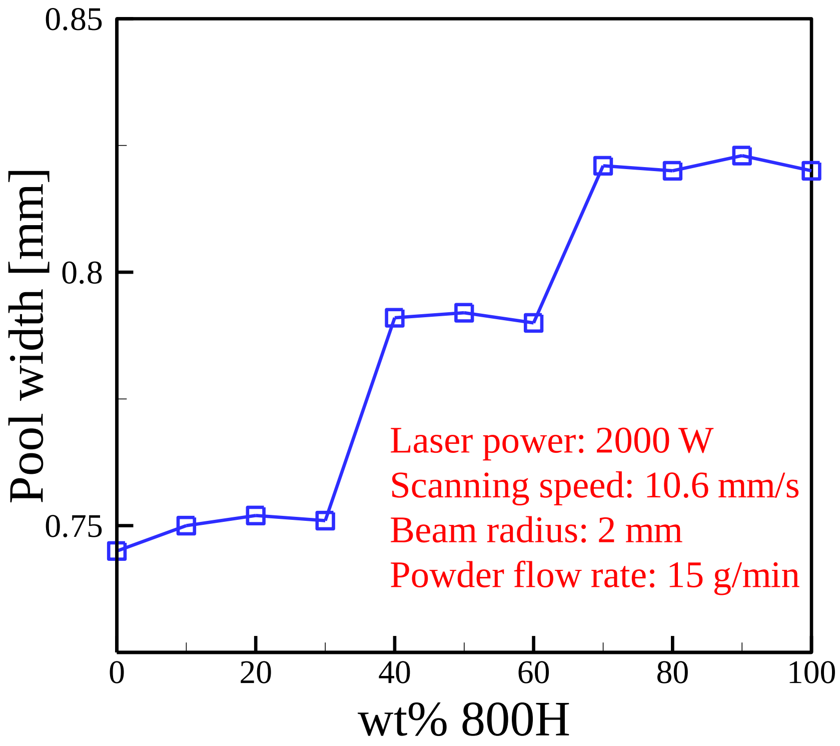
Material properties
Process parameters
Surrounding conditions

Temperature fields
Velocity distributions
Pool geometry







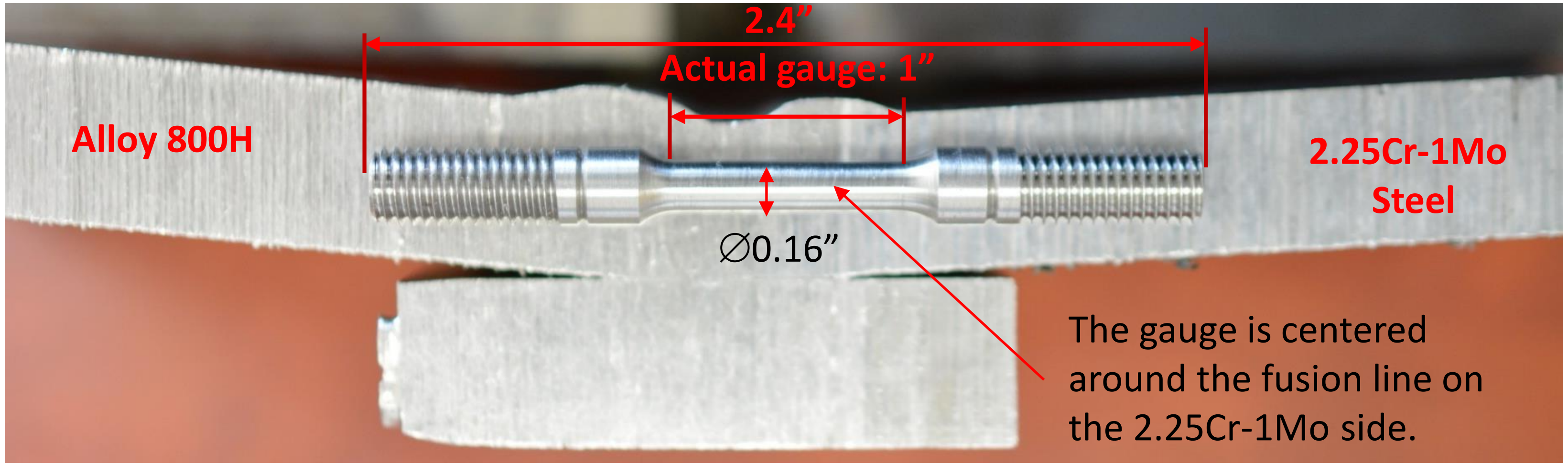


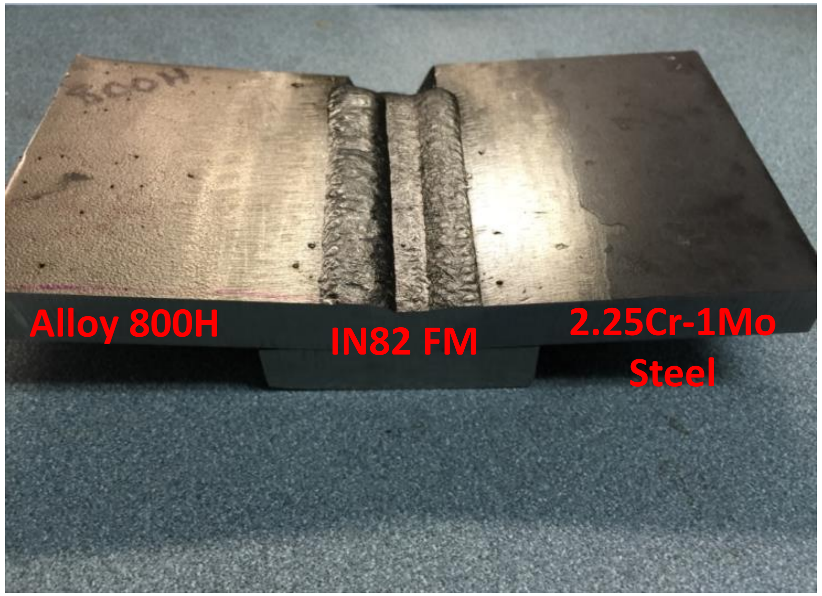
Mukherjee, Zuback, De & DebRoy. Printability of alloys for additive manufacturing. *Scientific Reports*. 2016.

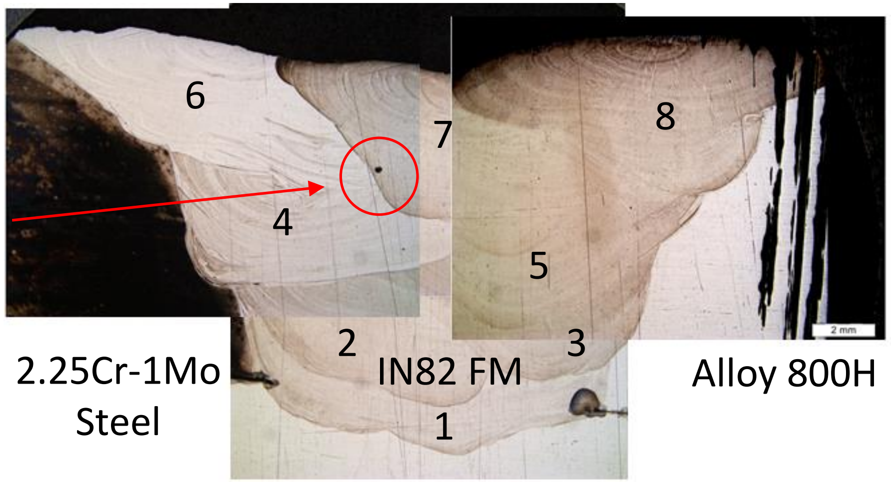
Welding Parameters

Gas Metal Arc Welding (GMAW):

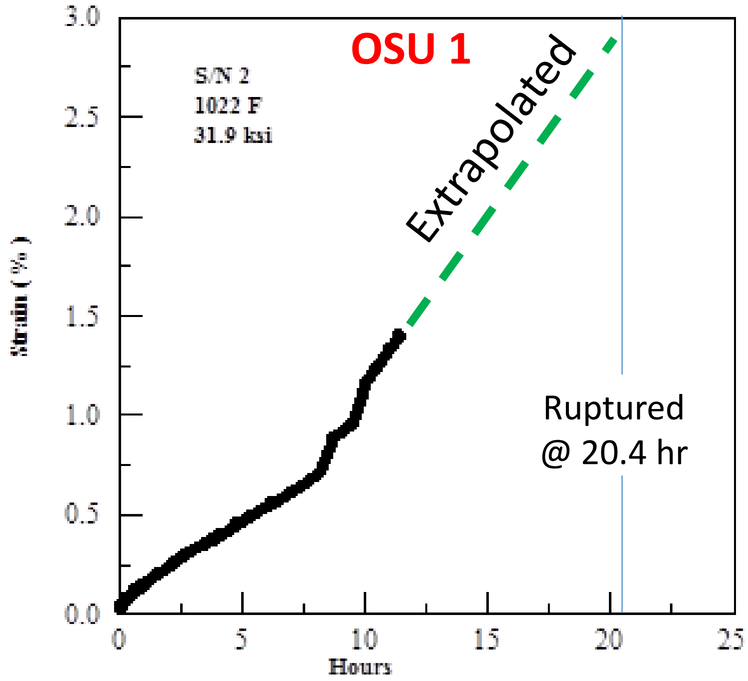
- Average voltage: 21V
- Average current: 210A
- Wire feed speed: 300 ipm
- Travel speed: 10 ipm
- Electrode stick out: 1.5 cm
- Weaving amplitude: 3 mm
- Drag angle: 5 deg.
- Preheat temperature: 280 °C
- Filler metal: FM 82
- Backing plate: Alloy 800H
- Shielding gas: Mixture of CO_2 and Ar

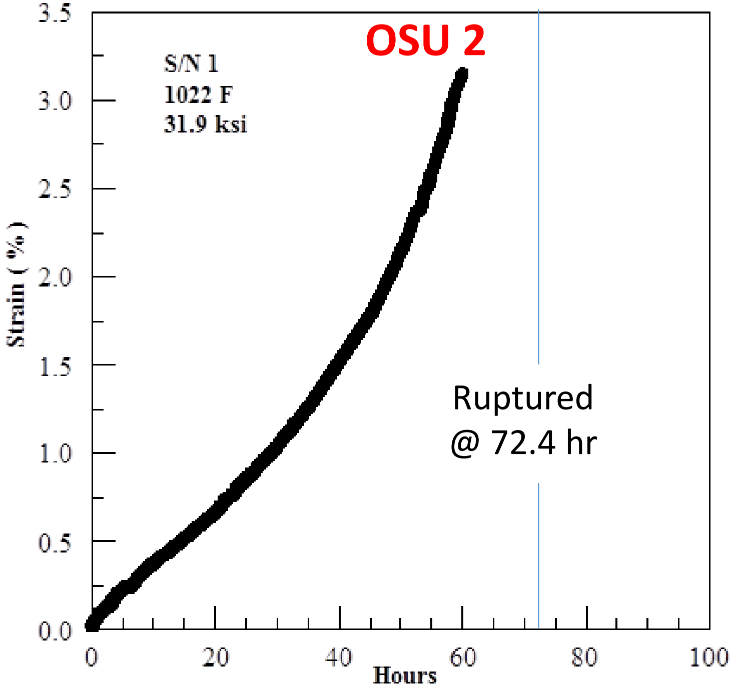




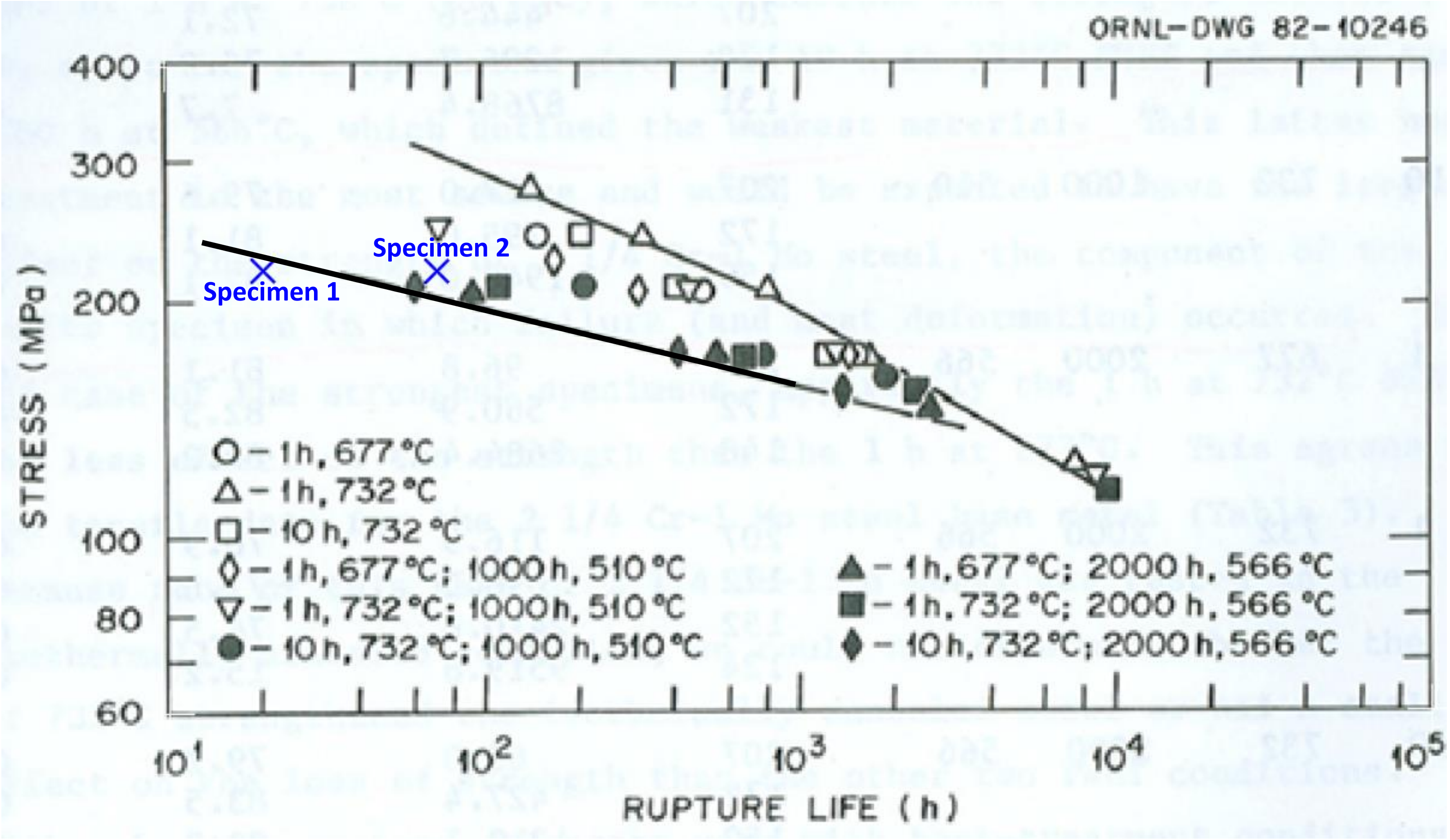


Creep Testing at 220 MPa and 550°C





Baseline creep data agrees well with previous literature



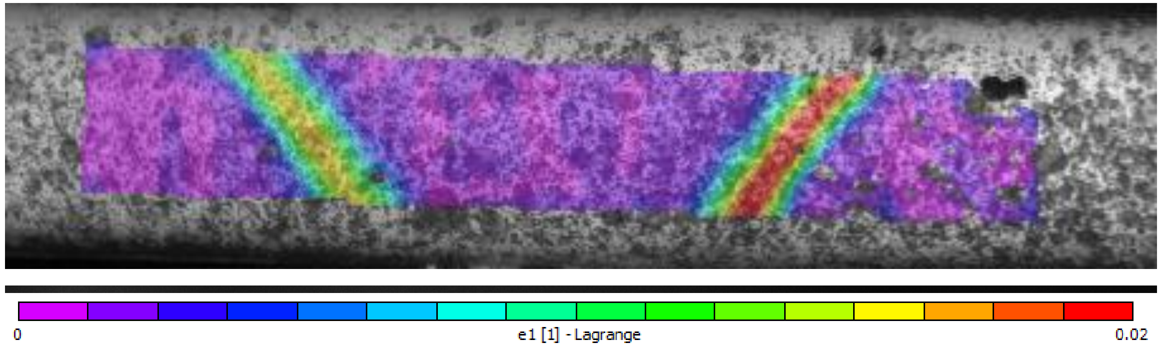
Klueh, K. L. and King, J. F. *Elevated temperature Tensile and Creep-Rupture Behavior of Alloy 800H/ERNiCr-3 Weld Metal/2.25Cr-1Mo Steel Dissimilar-Metal Weldments.* (ORNL, 1982)

Specialized Creep Testing

- Due to the inhomogeneity of the graded transition joints, traditional creep testing will not capture the creep behavior sufficiently
- Specialized creep testing using digital image correlation will show localized strain rates

Step 1: Dissimilar metal weld

- Test weld with same process and creep test parameters used at OSU
- Compare results with baseline data to validate the method
- Identify regions of localized strain



Creep strain map of a Grade 91 cross-weld sample showing localized deformation

Step 2: Graded transition joint

- Test a graded transition joint fabricated at PSU using the in house DED-AM machine
- Compare results with baseline data to see anticipated improvement in creep performance
- Identify regions of localized strain

SS316/ T22 DMW sample image after 378 hours creep testing

Acknowledgements

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