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Functionally Graded Materials Between Ferritic and Austenitic Alloys using Additive Manufacturing

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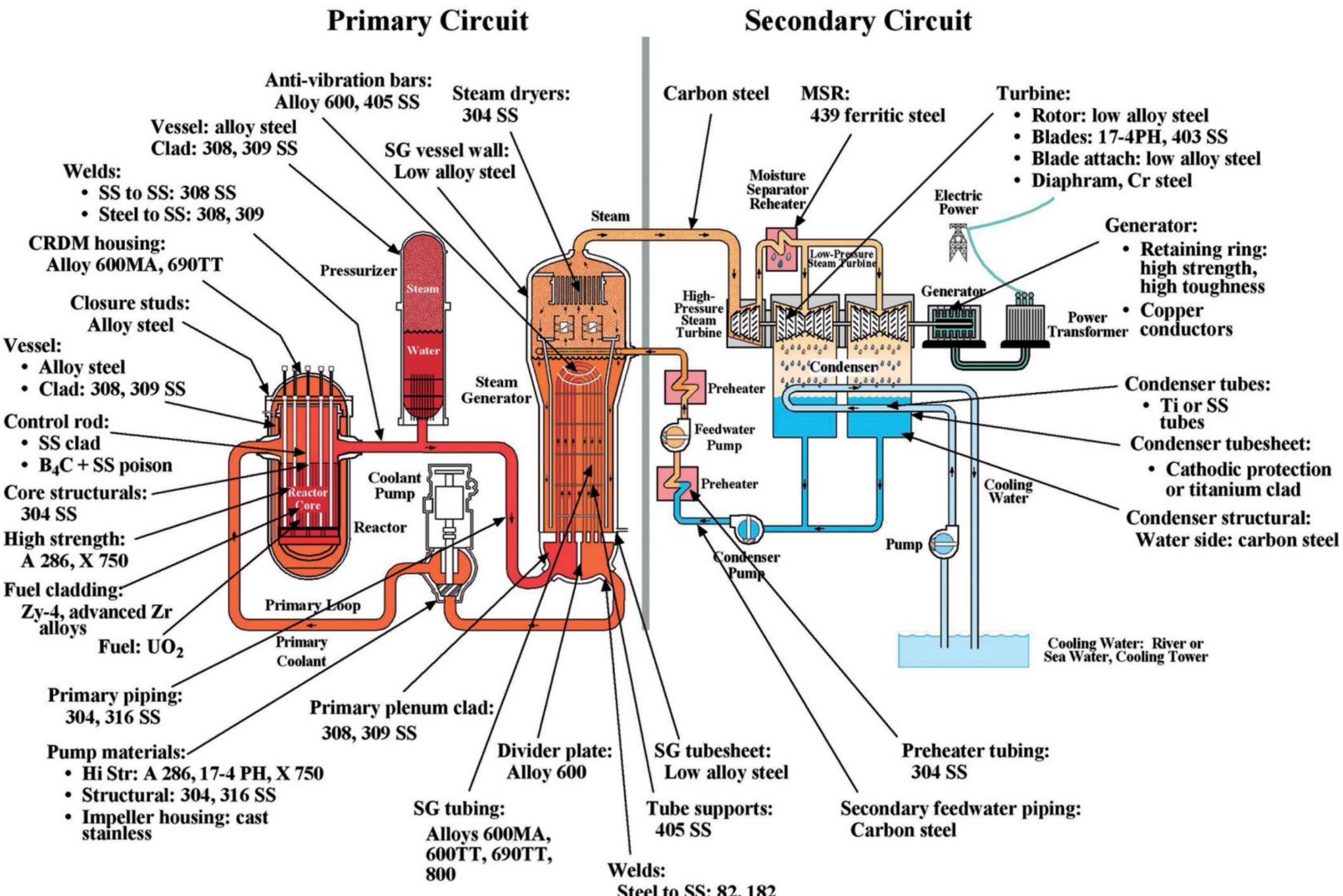
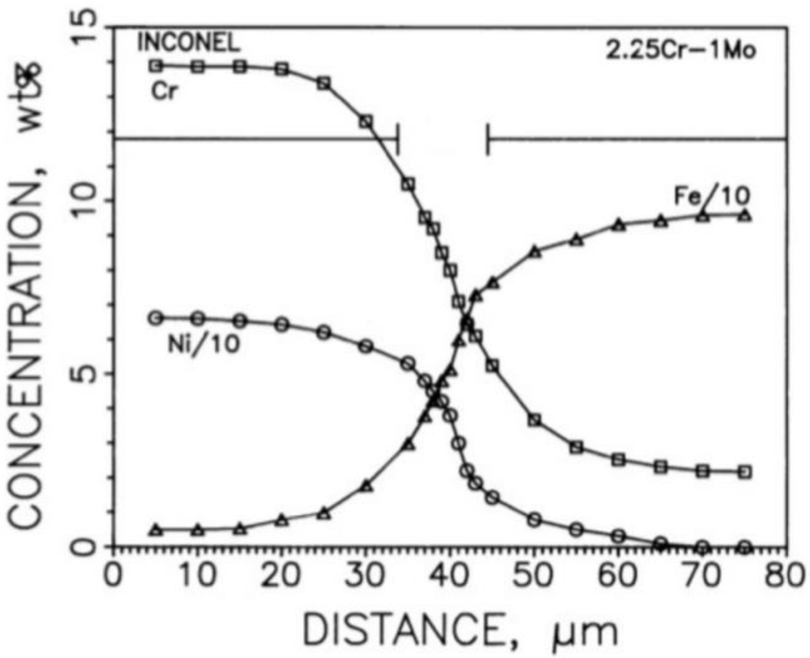
Materials in nuclear power plants



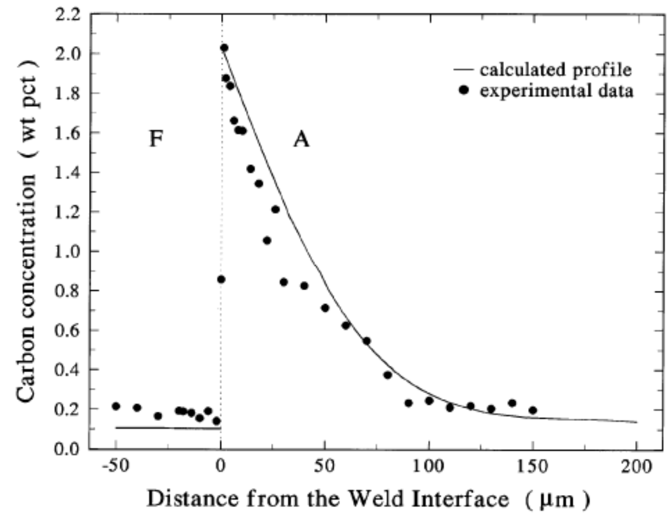
T. Allen et al., *Materials Today,* 13(12) (2010) 14-23.

Dissimilar metal welds between ferritic to austenitic materials in nuclear power plants

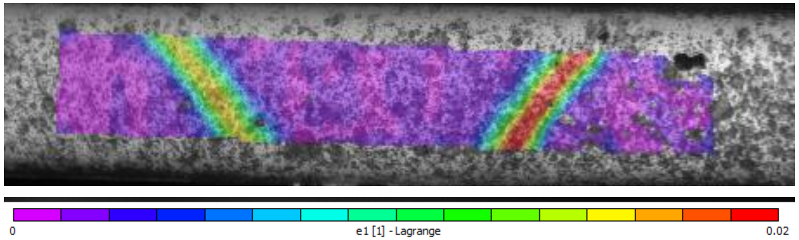
Problem: Carbon diffuses from the ferritic steel towards the austenitic alloy



Laha, *Metall. Mater. Trans A*, 2001



Huang, *Metall. Mater. Trans A*, 1998



Courtesy of creep testing at ORNL

Consequence: Carbon depleted zone in steel → Poor creep performance

Solution: Reduce carbon diffusion to improve creep performance

Approach

Thermodynamic and kinetic models for designing composition profiles that minimize carbon diffusion

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Fabricate transition joints by additive manufacturing

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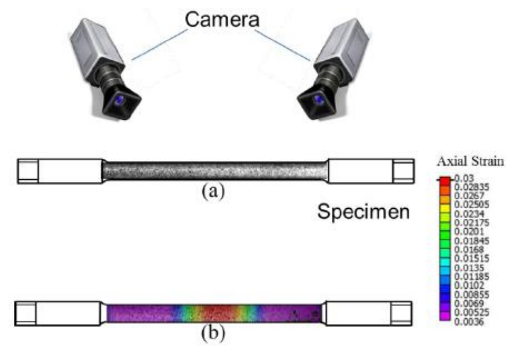
Test and characterize fabricated joints



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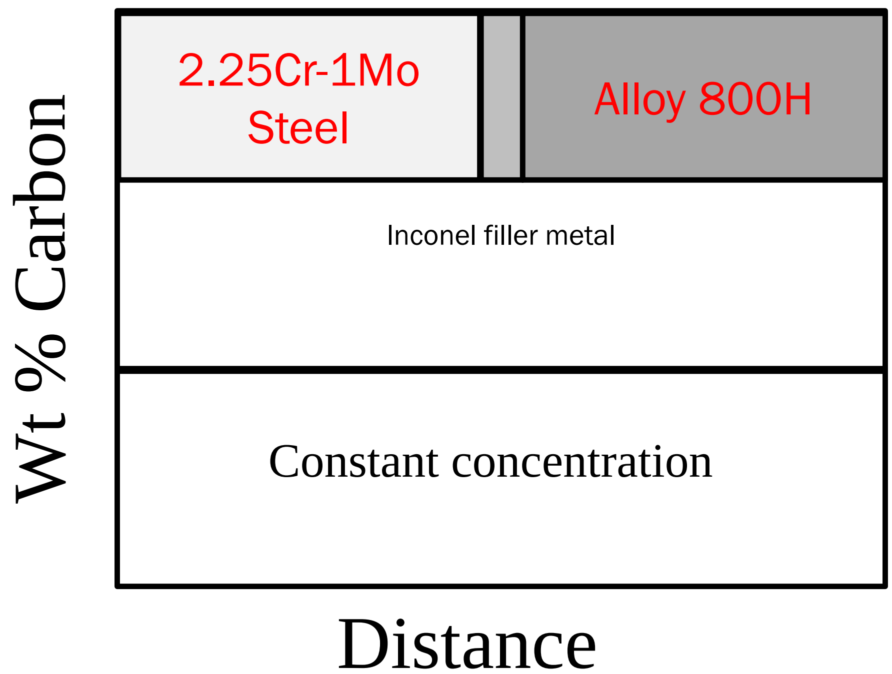
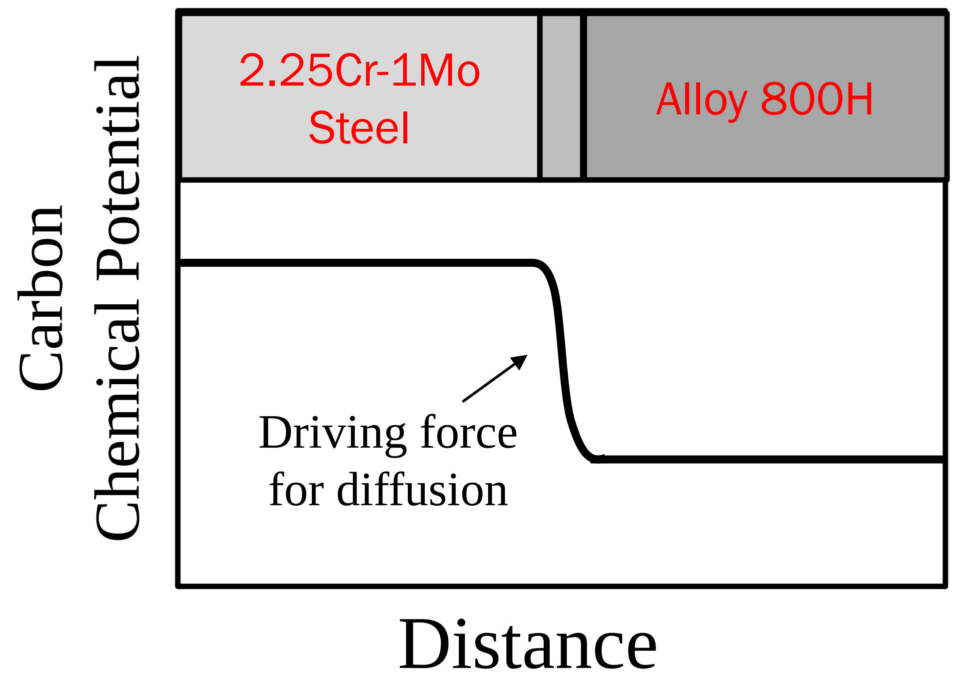
What causes carbon diffusion?

Uniform carbon concentration → Chemical potential gradient





Fick's first law of diffusion

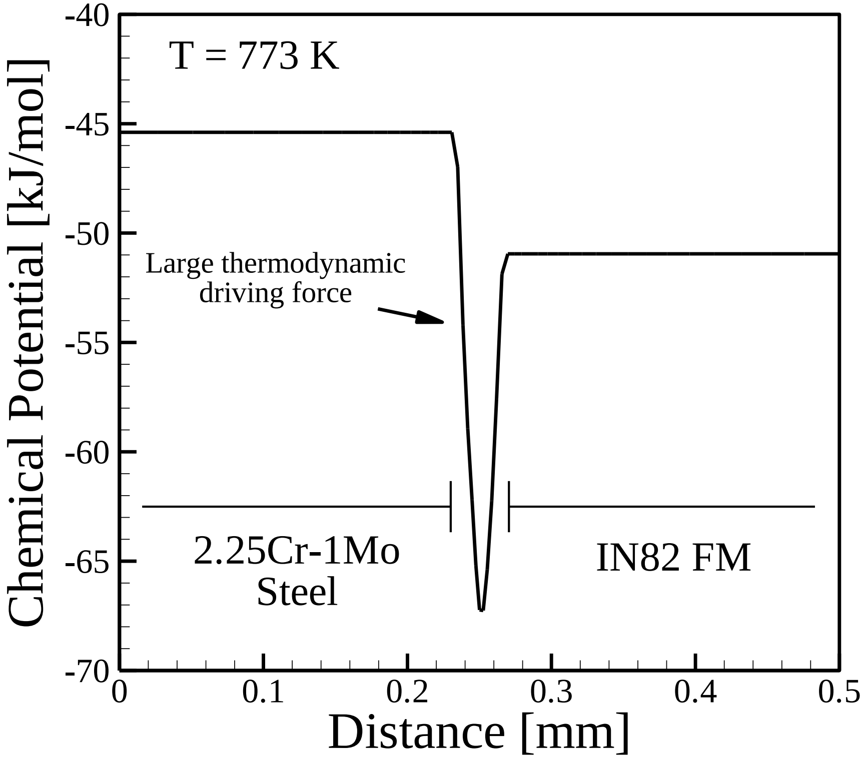
$$J_i = -D_i \frac{dc_i}{dx} \quad \Rightarrow \quad J_i = -\frac{L_i}{T}\frac{d\mu_i}{dx}$$

Depends on alloying elements

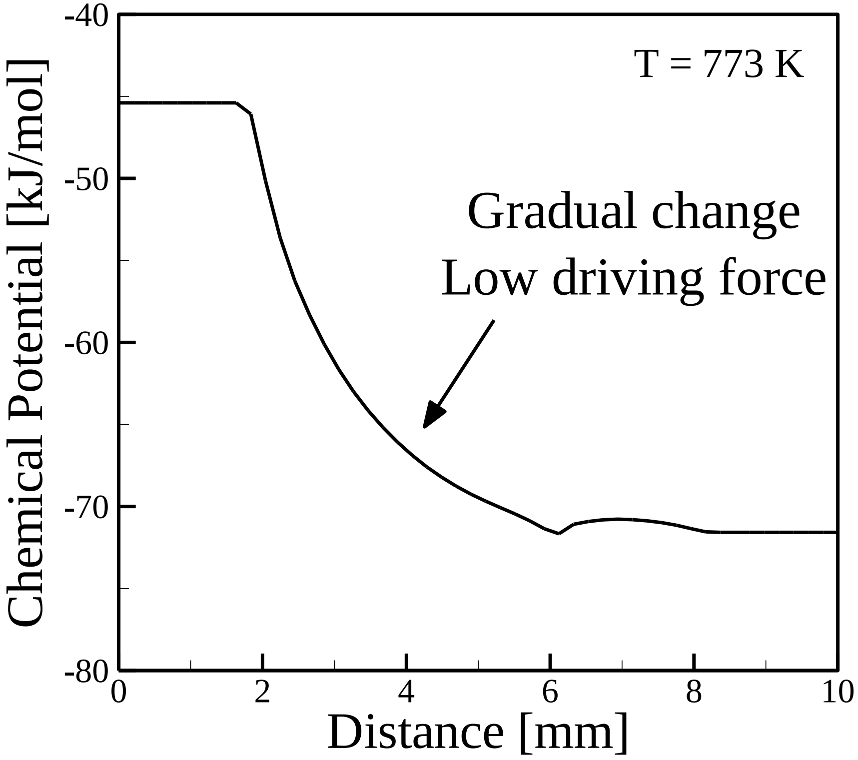
Thermodynamic modeling

Goal: Reduce carbon chemical potential gradient

Dissimilar metal weld



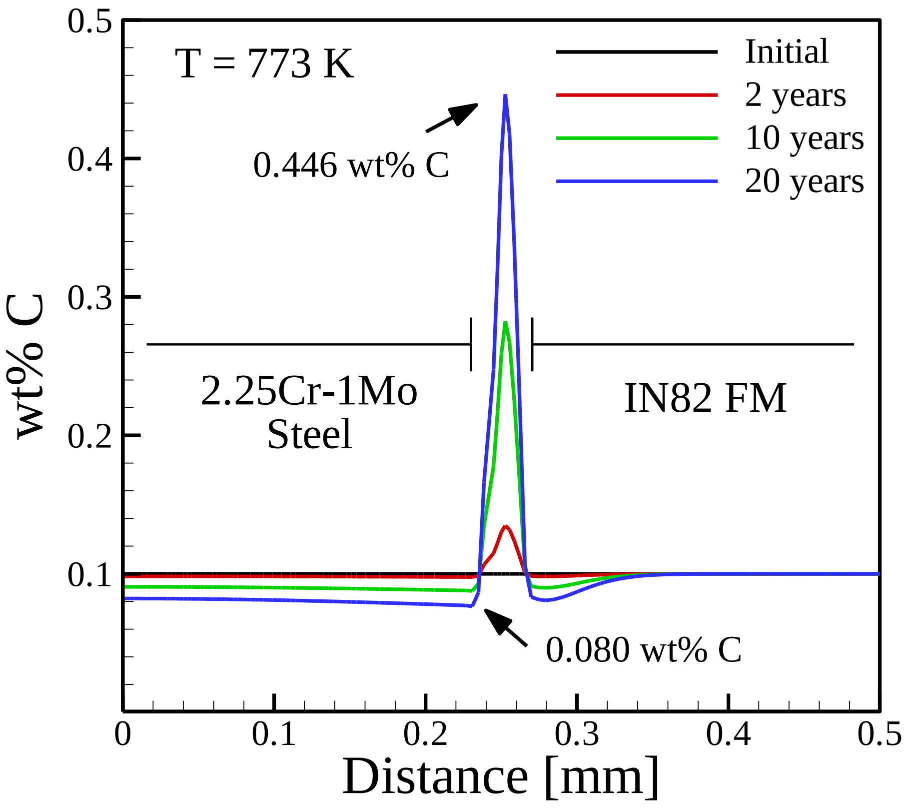
Functionally graded material



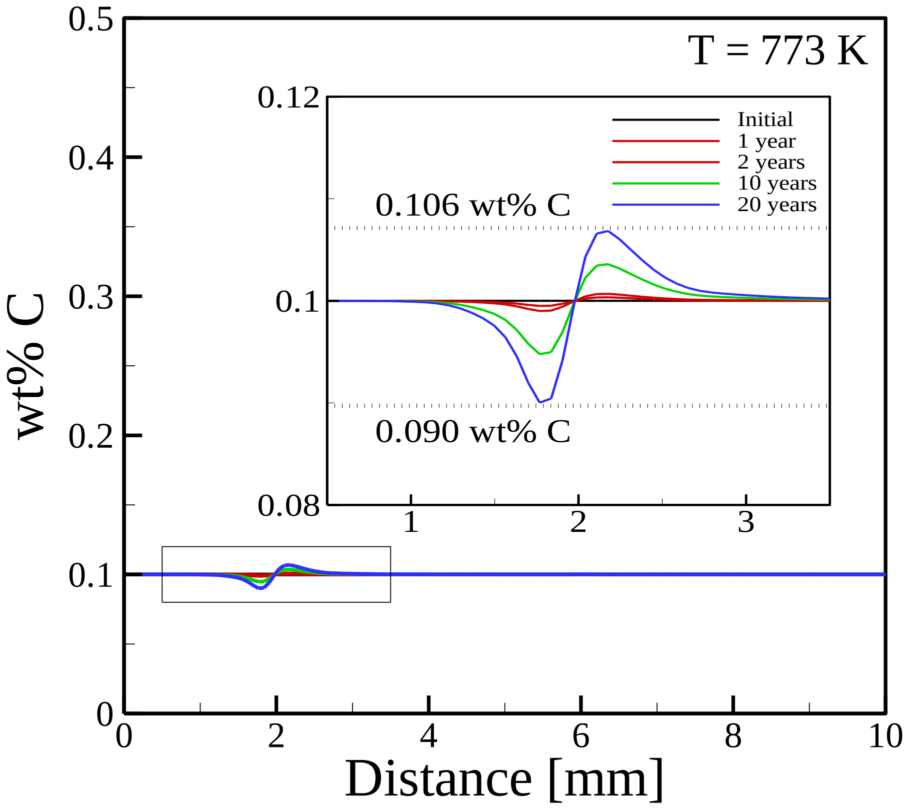
Kinetic modeling

Goal: Predict carbon migration after years of service

Dissimilar metal weld

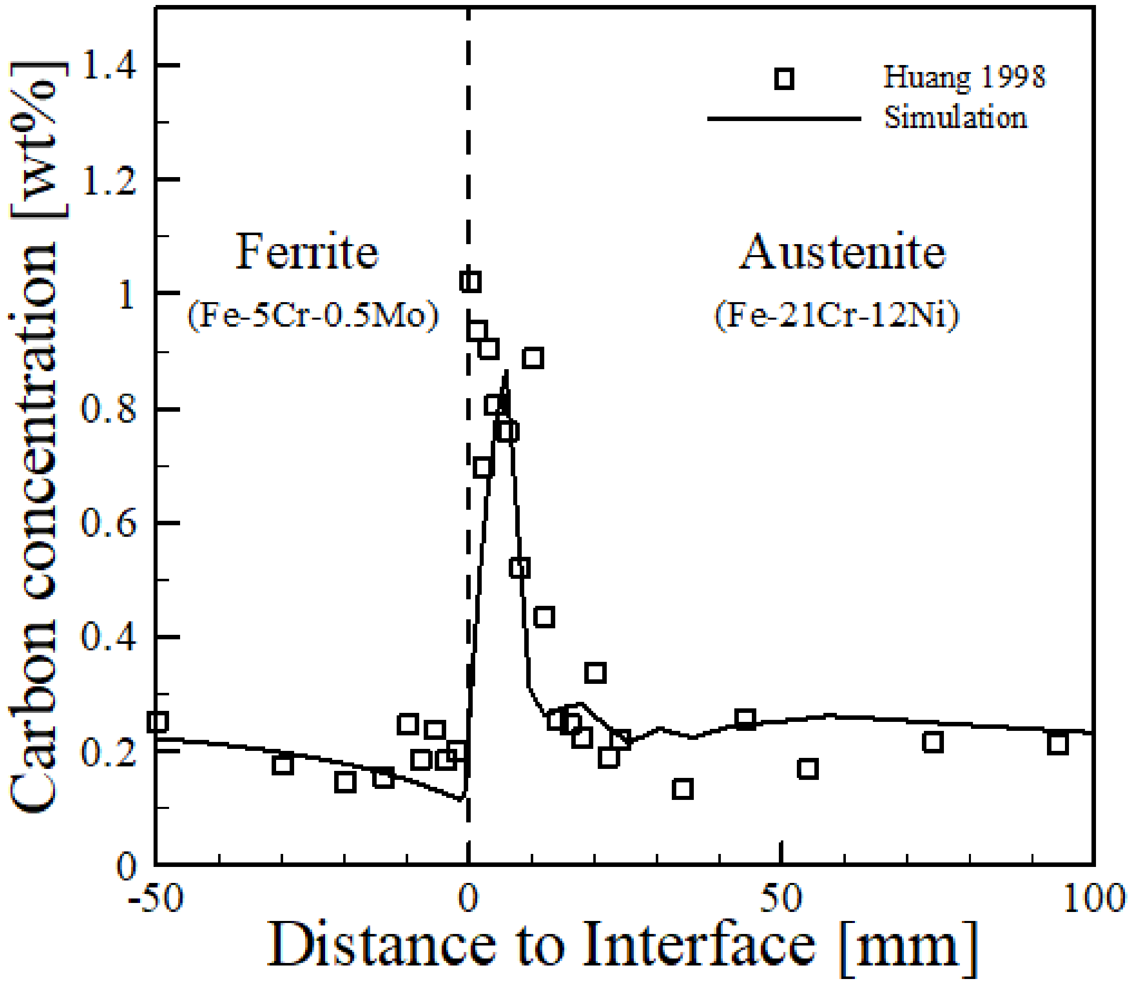


Graded transition joint



Diffusion model validation

Testing calculations against independent experimental data



Experimental data from M.L. Huang, L. Wang, Metall. Mater. Trans A, 29 (1998) 3037-3046

<u>Comparison</u>

- Good agreement between calculated and measured carbon diffusion profiles
- Accumulation of carbon in austenitic material along interface
- Carbon depletion in ferritic material along interface
- Confidence to apply the model to functionally graded materials

Fabrication of functionally graded specimens using additive manufacturing

Directed energy deposition

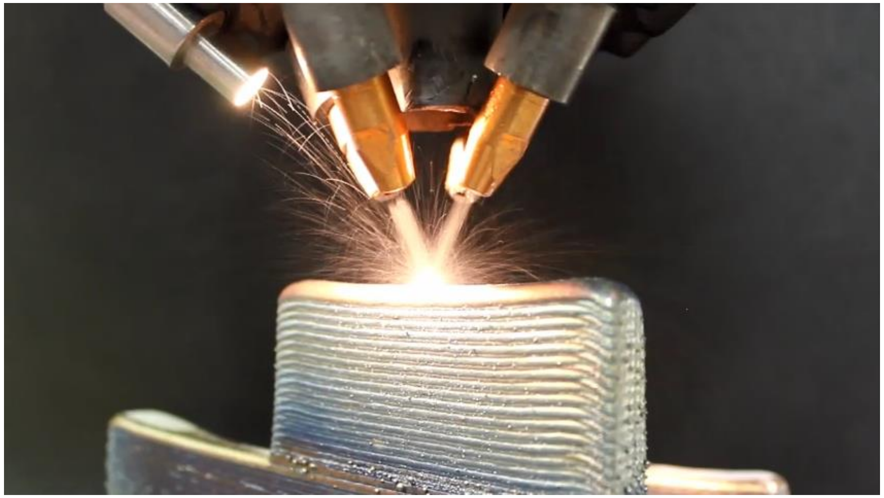
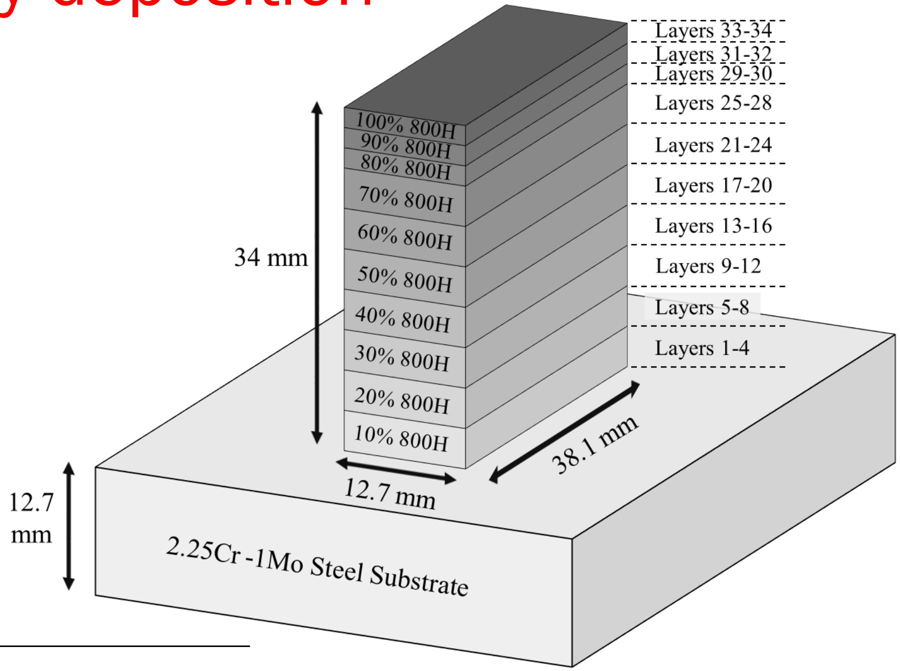


Photo courtesy of PSU ARL



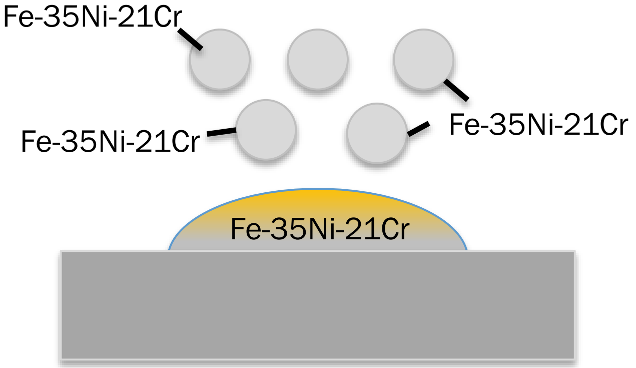
	Wt% of element										
Powder	Al	Cr	Fe	Mn	Ni	Si	Ti	C	O	P	S
Pyromet® 800	0.38	21.0	Bal.	0.88	34.0	0.62	0.41	0.095	0.015	0.003	0.006
Fe	-	-	Bal.	-	-	-	-	0.005	-	-	0.016
Cr	<0.01	Bal.	0.07	-	-	<0.01	-	0.004	0.43	0.0013	0.023

Pre-blended powders were entered into the powder feeder at increments of 10% 800H

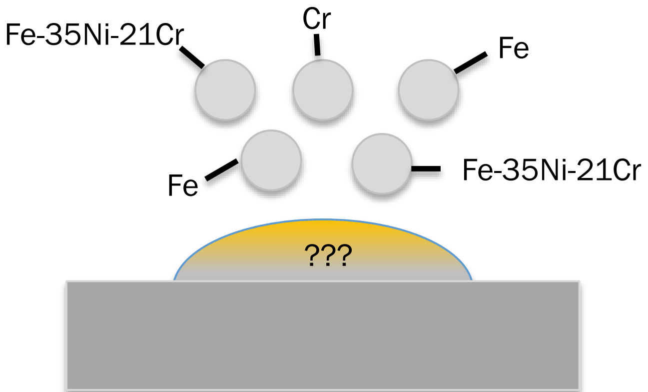
Controlling chemical composition profiles

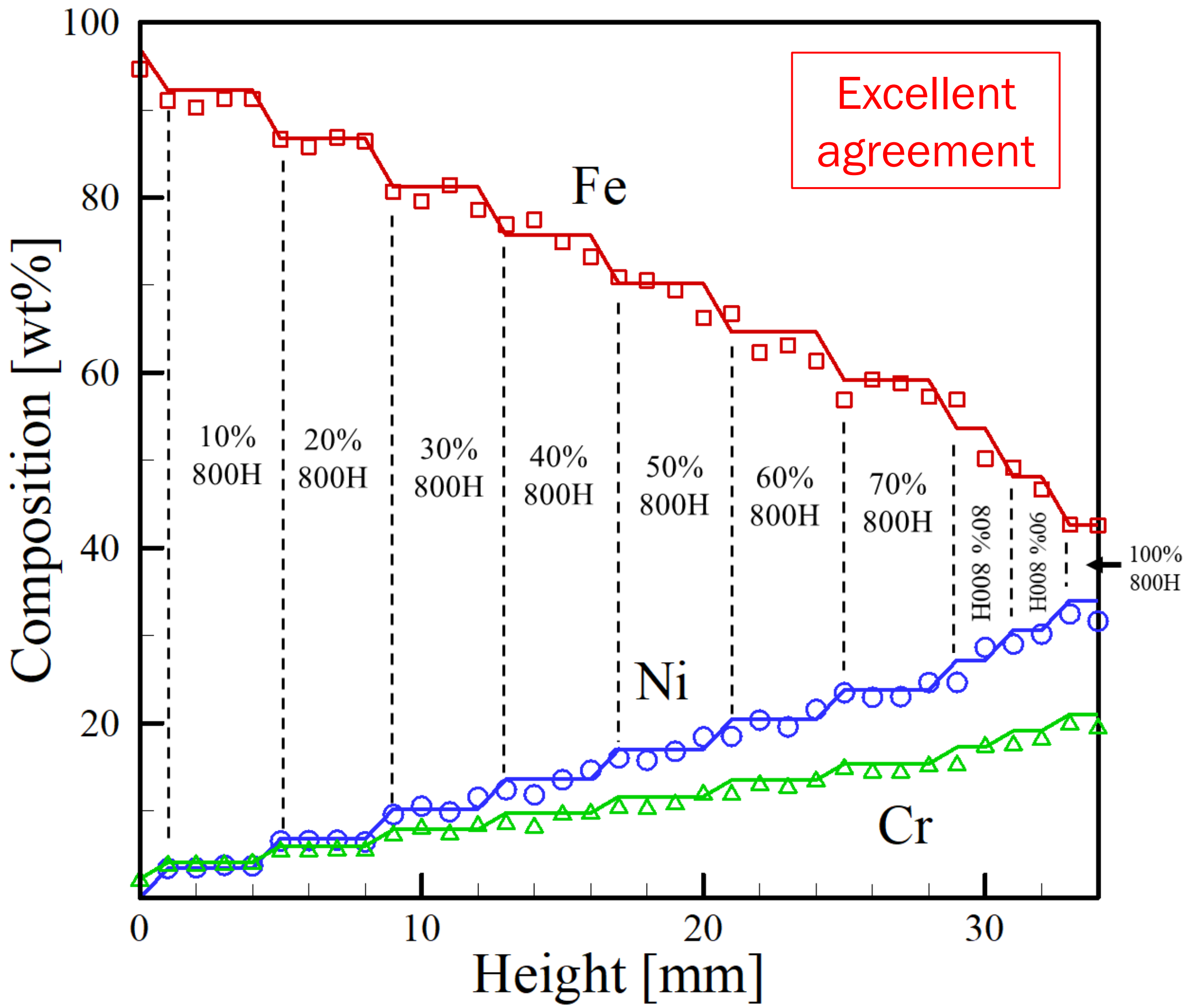
Can composition be controlled using pre-blended powders?

Using pre-alloyed powder

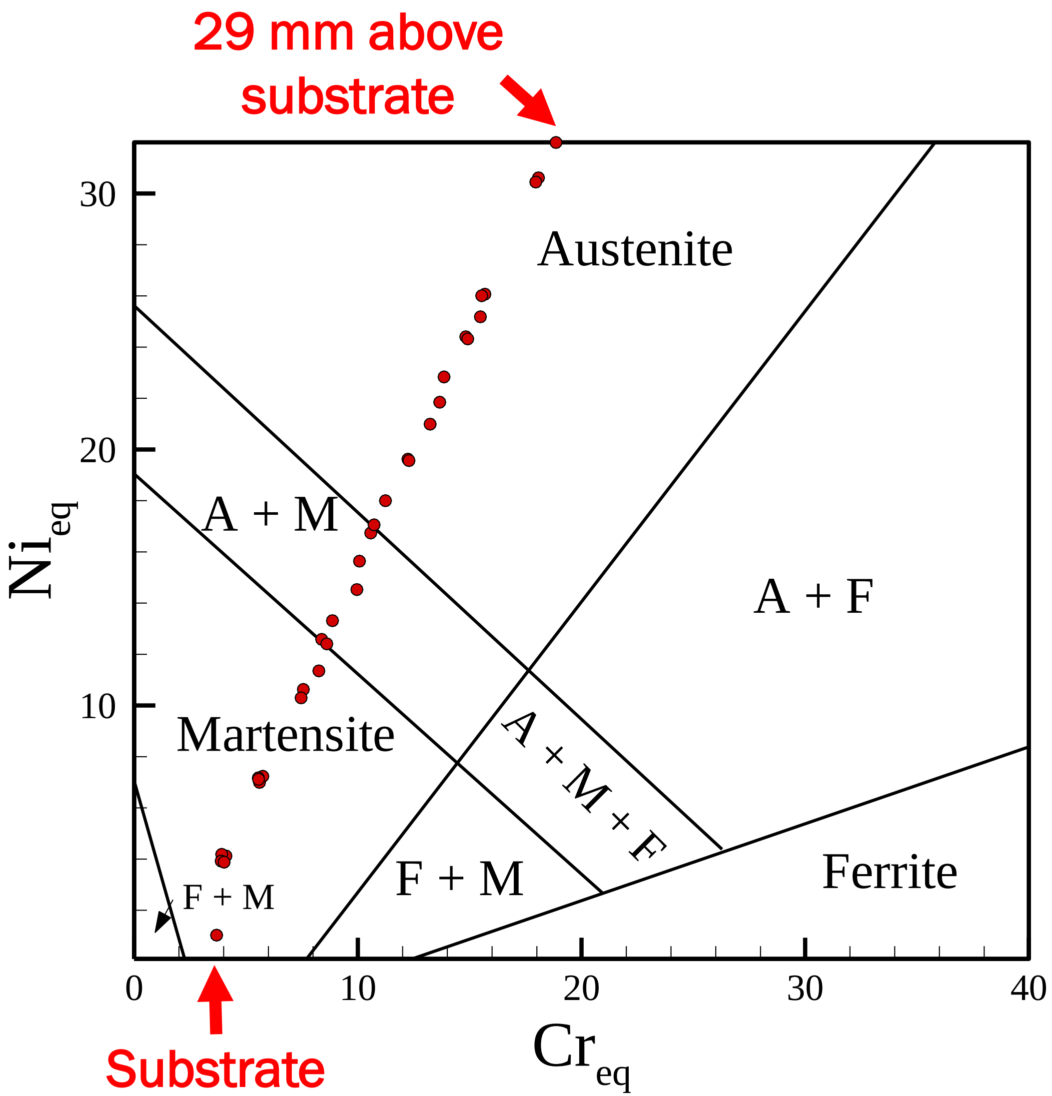


Using blended powders





Microstructure Prediction

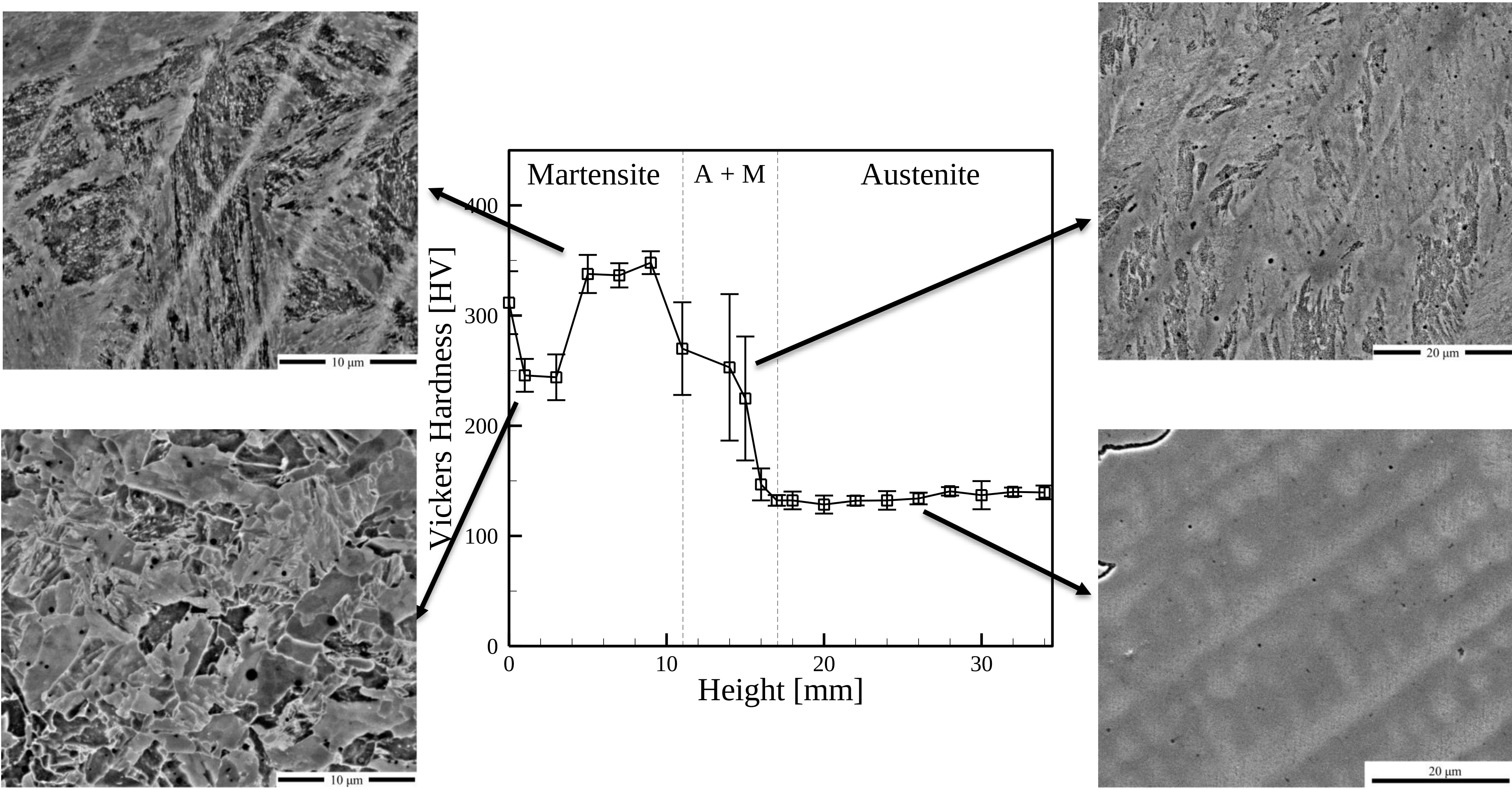


Schaeffler Constitution Diagram

- 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
- Measured chemical compositions from EPMA were used to calculate Ni_{eq} and Cr_{eq}
- Here, a martensitic to austenitic microstructure is predicted

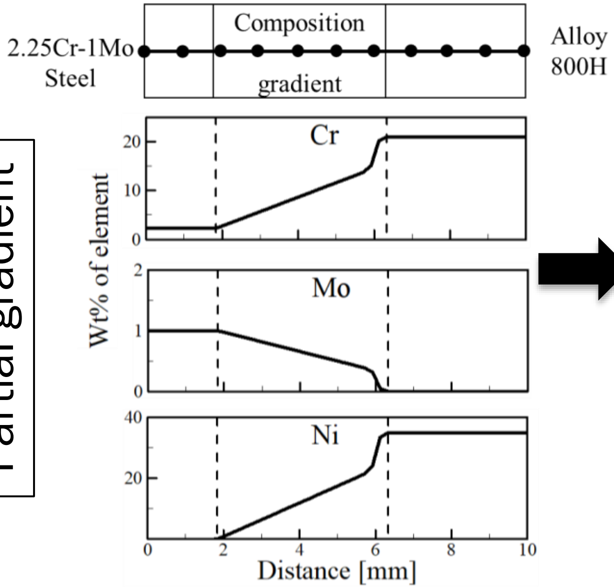
Microstructural characterization

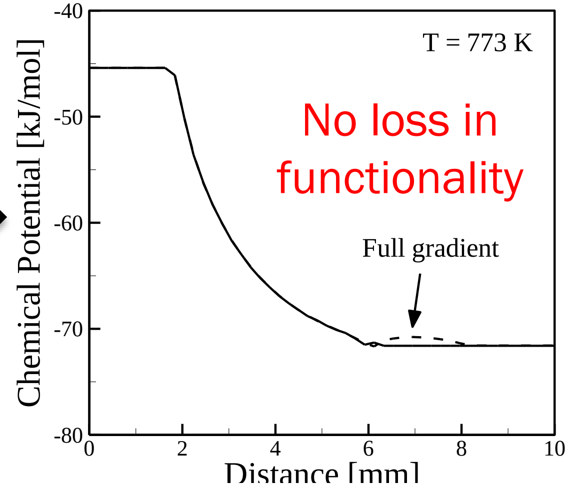
Significant changes in microstructure and microhardness are observed

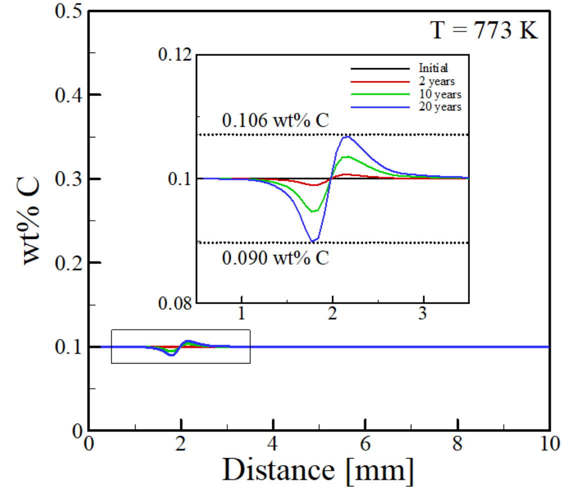


Is a full composition gradient necessary?

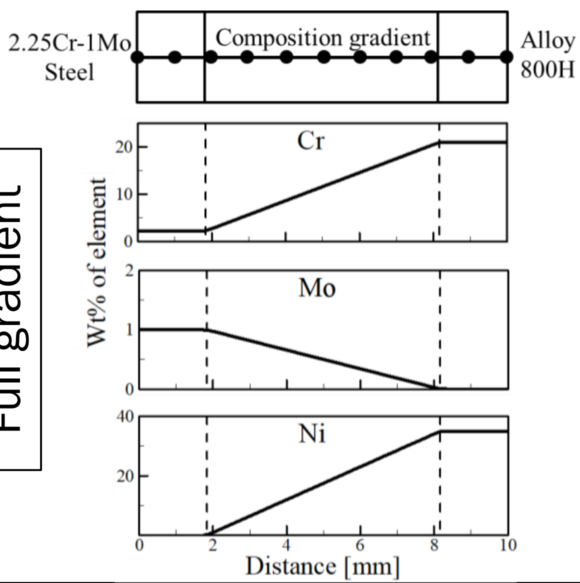
Partial gradient

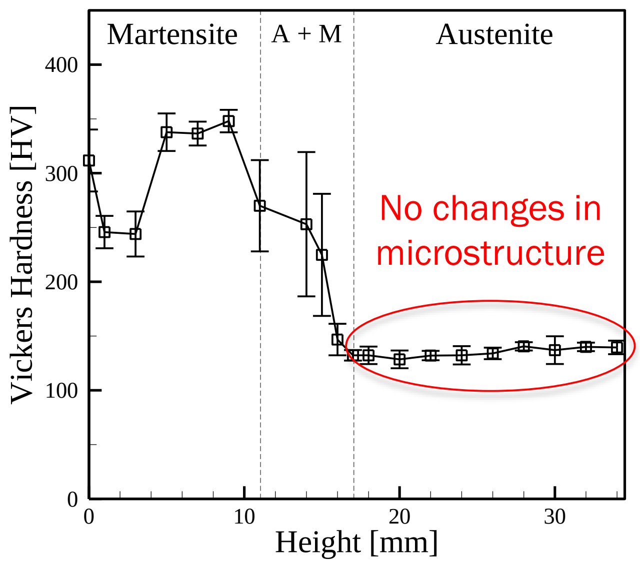






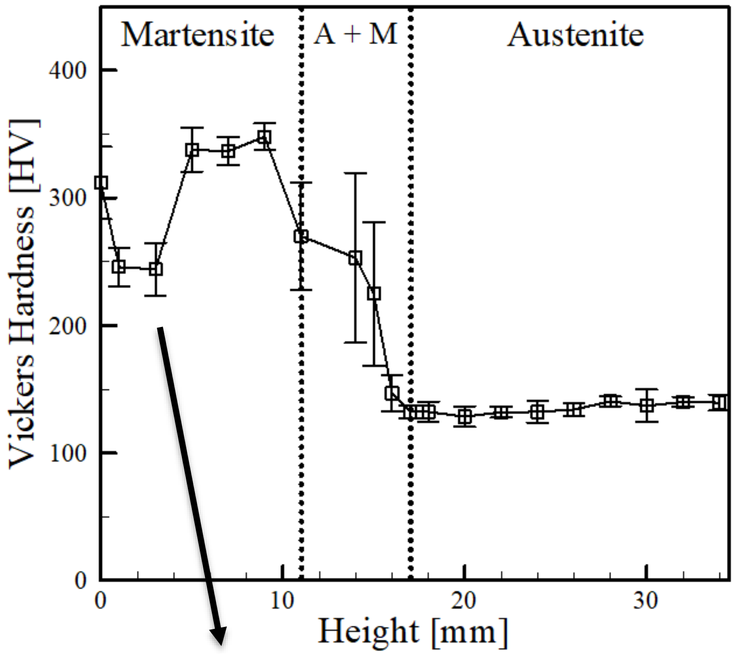
Full gradient

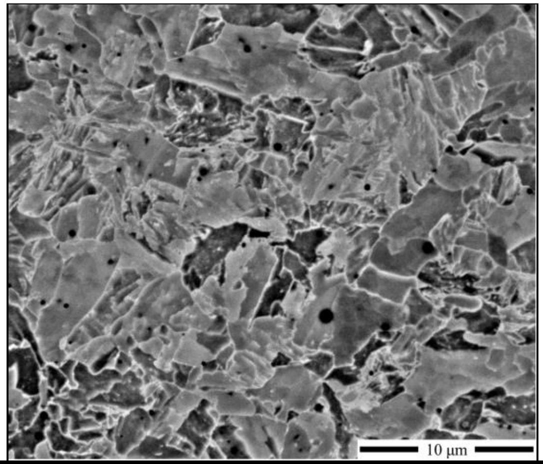


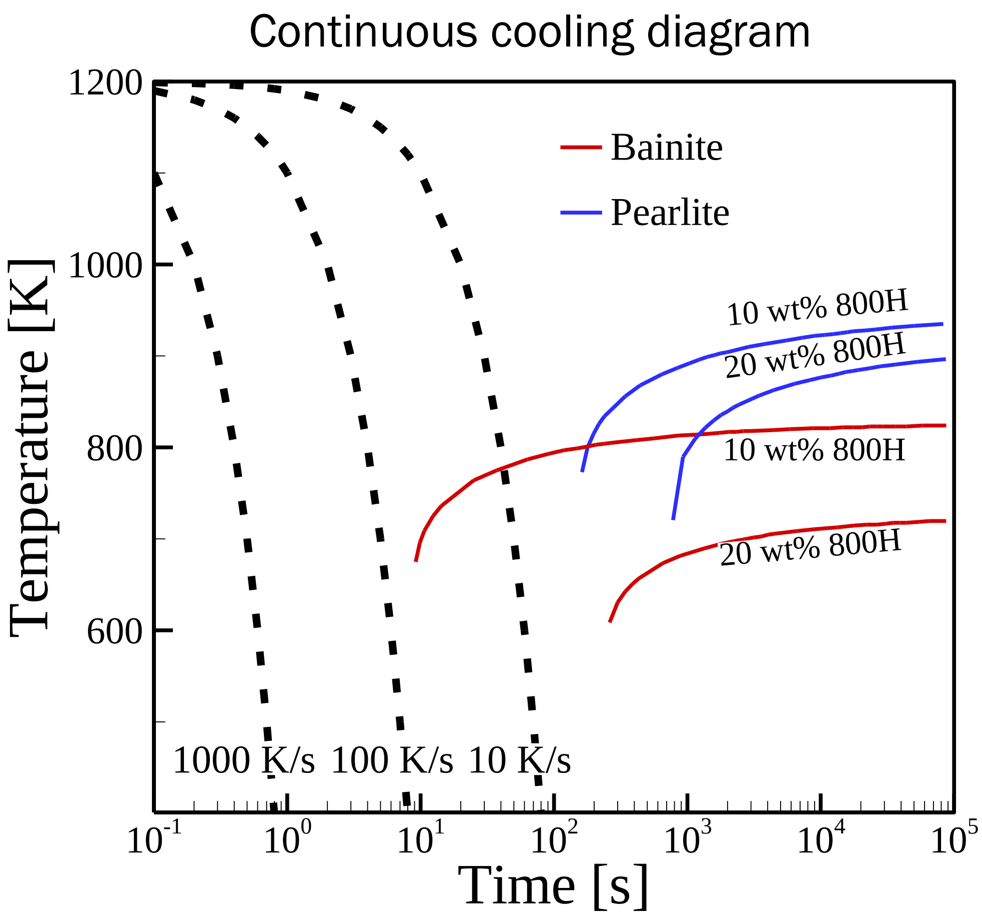


No benefits in compositional grading once the microstructure becomes fully austenitic

Soft zone formation near baseplate

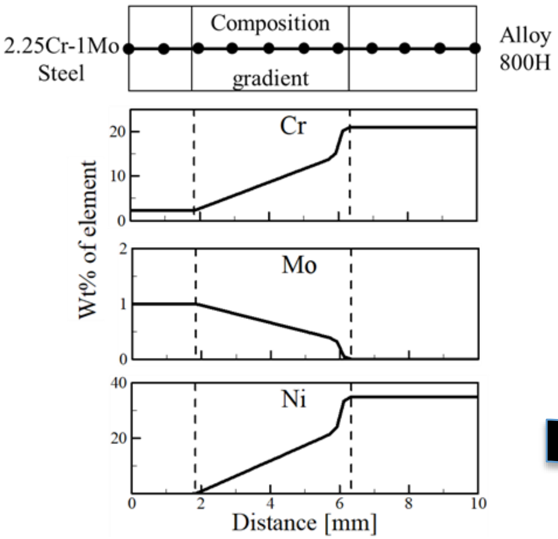


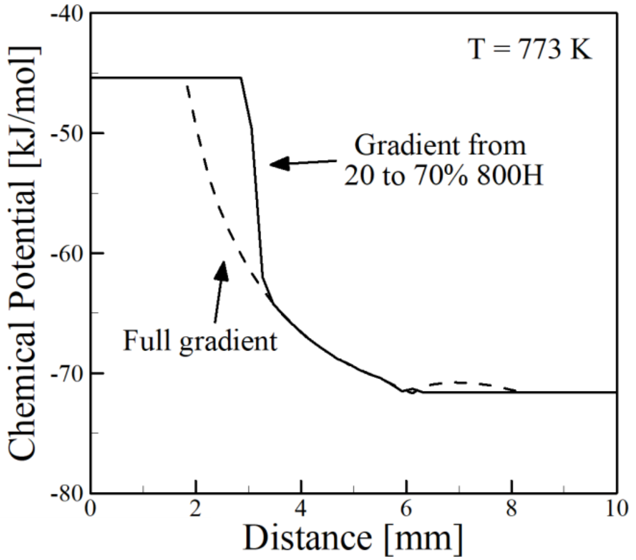




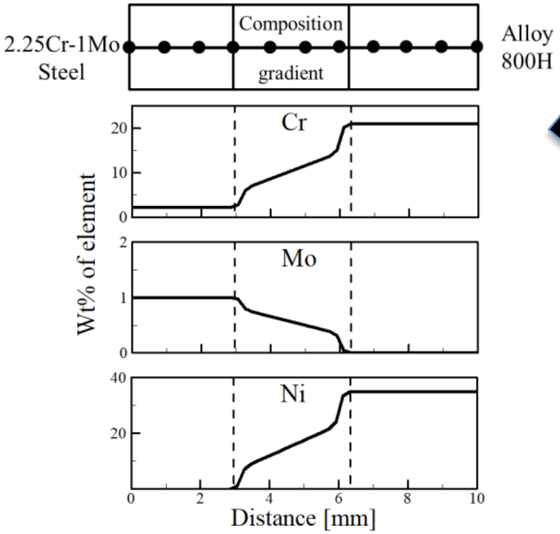
Bainite is the microconstituent *most likely* to form during cooling other than martensite

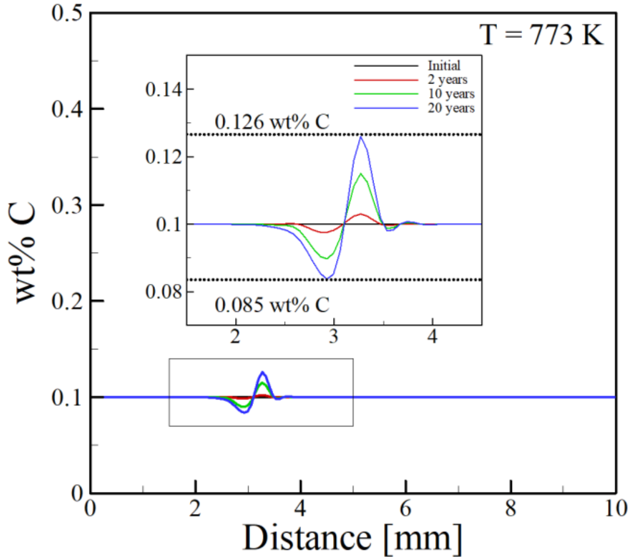
What if the soft zone is excluded?





Increase in the carbon chemical potential near the deposit/baseplate interface



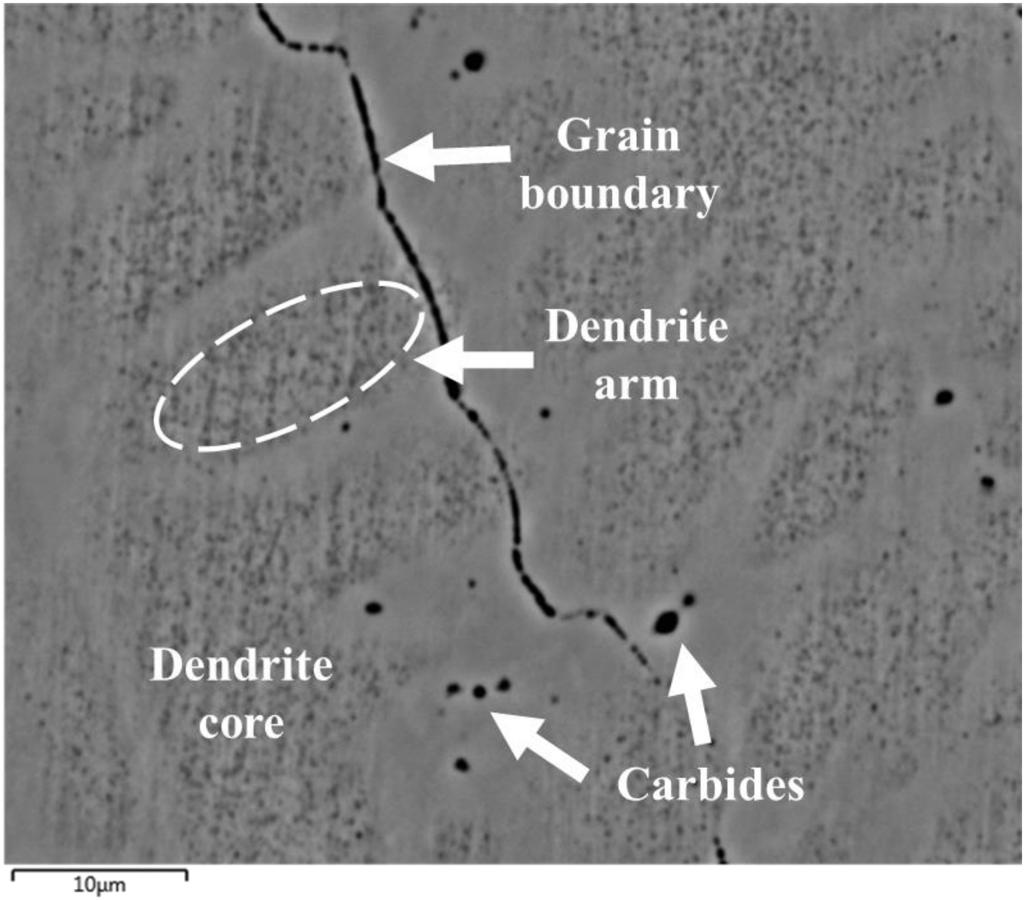


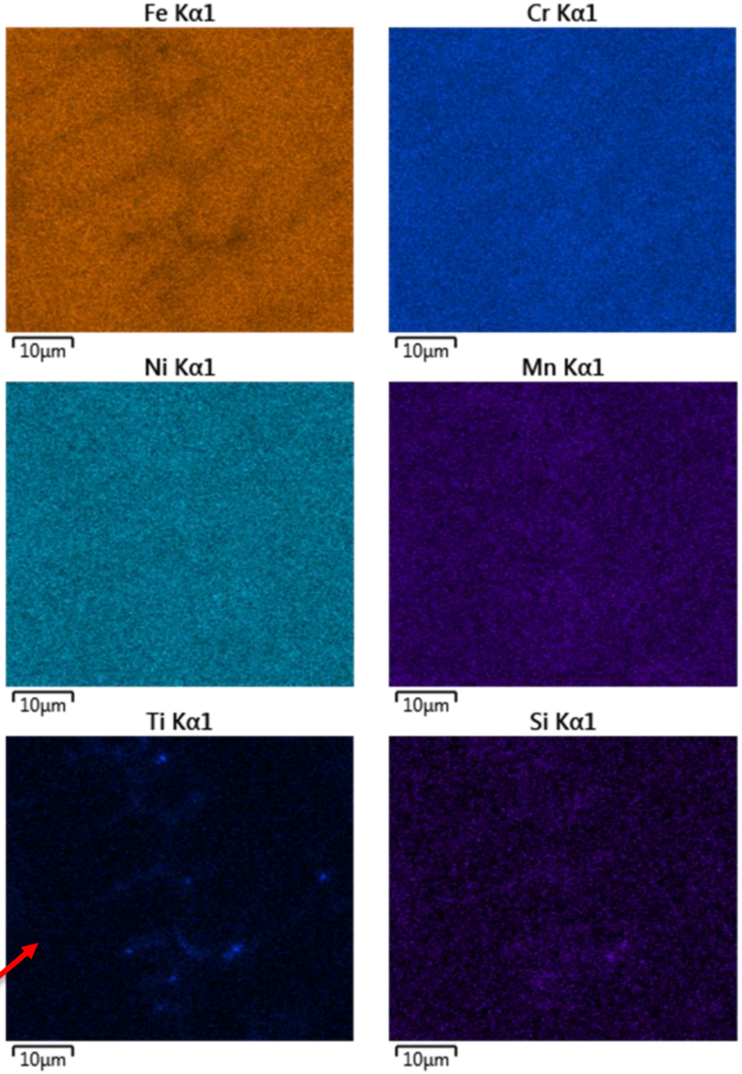
More carbon diffusion after years of service compared to a gradient starting at 10% 800H

Secondary phase formation

Experimental observations

SEM with EDS composition maps



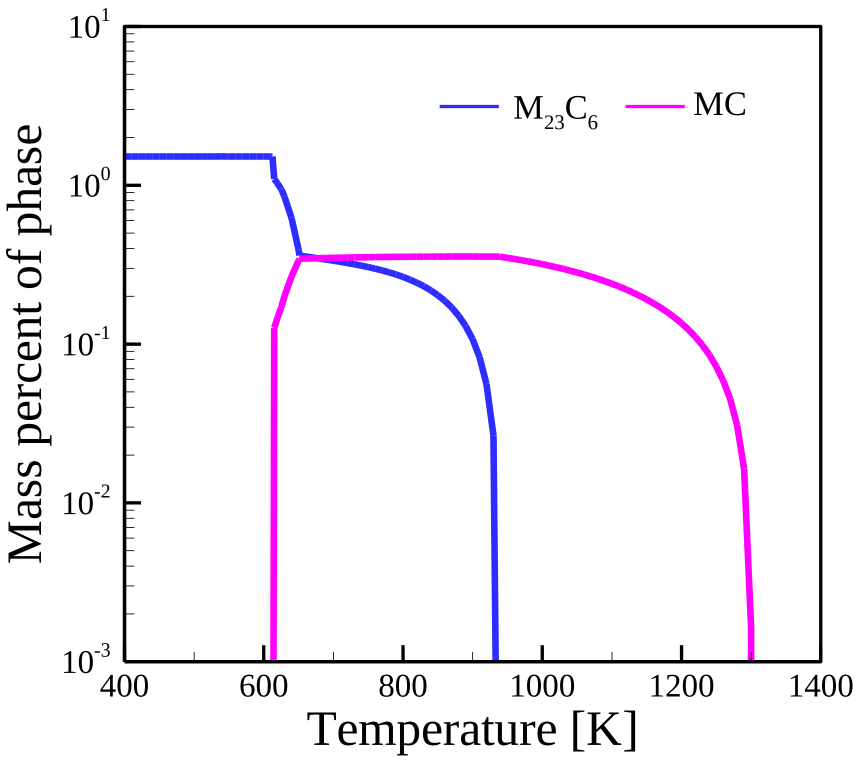


Ti-rich particles near grain boundaries/interdendritic regions

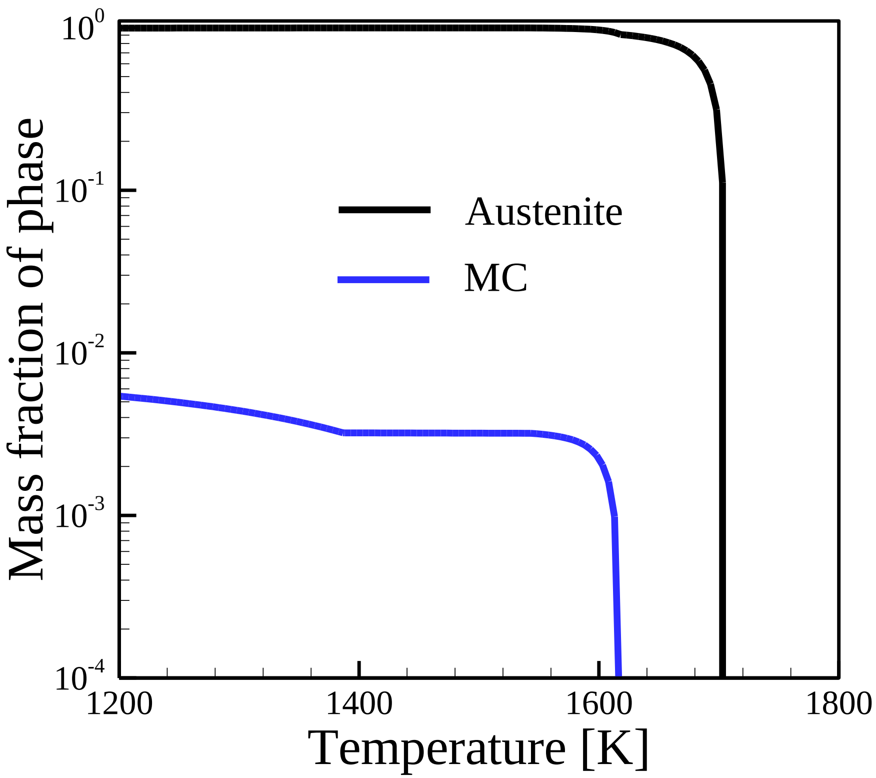
Secondary phase formation

Calculations

Equilibrium secondary phases



Scheil-Gulliver solidification



Although both M23C6 and MC carbides are stable at operating temperatures (773K), only MC is predicted to form when considering solidification

Summary

- Carbon diffusion across dissimilar metal welds between ferritic and austenitic material leads to premature failure
- Functionally graded materials drastically reduce carbon migration by reducing the carbon chemical potential
- An appropriately graded transition joint will take approximately five times longer to deplete the same amount of carbon as a dissimilar weld
- Kinetic considerations are essential for the design of functionally graded materials
- Tradeoffs exist between microstructure and designed functionality

Acknowledgements

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