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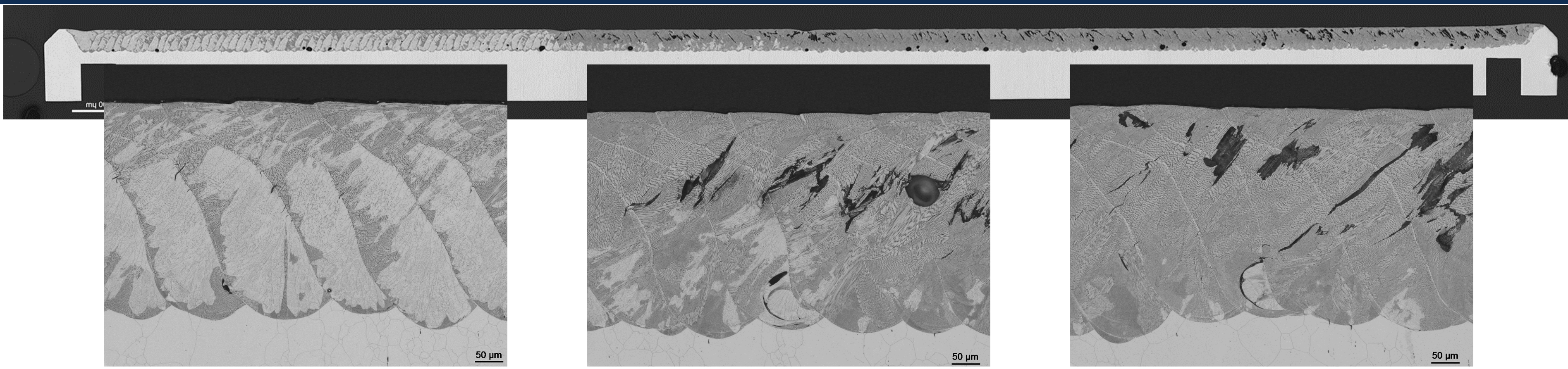

Effect of Multiple Reweld Passes on the Solidification and Cracking Response of 304L

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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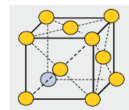
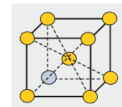
Alloy Chemistry Determines 304L Solidification Mode

Primary Austenite

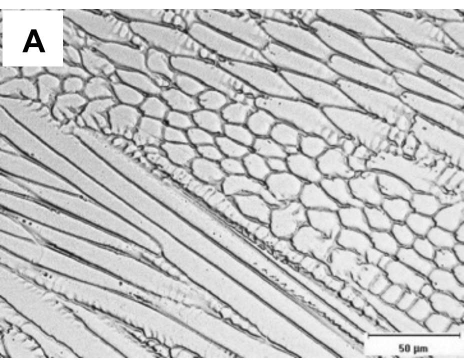


- Increased solidification cracking concern
  - Less tolerant of impurities (namely phosphorus + sulfur). Requires 'clean' alloys to preclude cracking.
  - Less tolerant of restraint

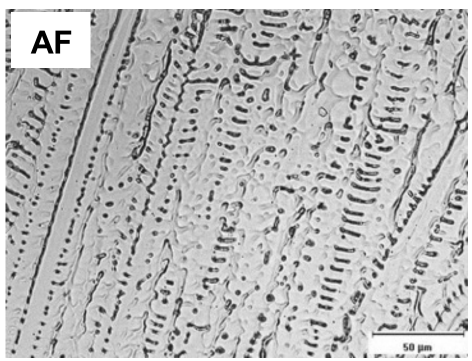
Primary Ferrite



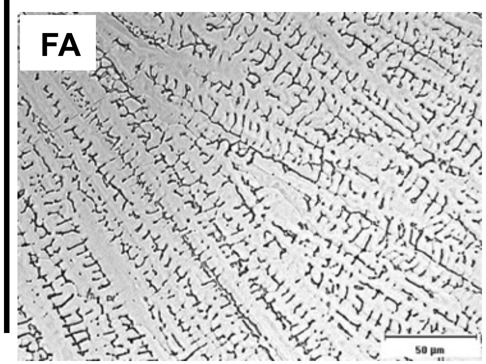
- Desired solidification mode
  - Increased resistance to solidification cracking
  - More tolerant of restraint and impurity elements



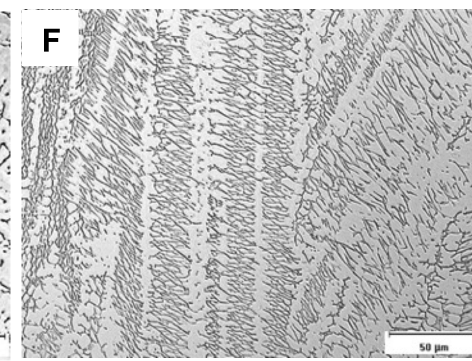
L → L + A → A



L → L + A → L + A + $(A+F)_{eu.}$ → A + $F_{eu.}$



L → L + F → L + F + $(A+F)_{eu./per.}$ → A + F



L → L + F → F → A + F

Austenite Promoters

Ni, C, N, Mn, Cu

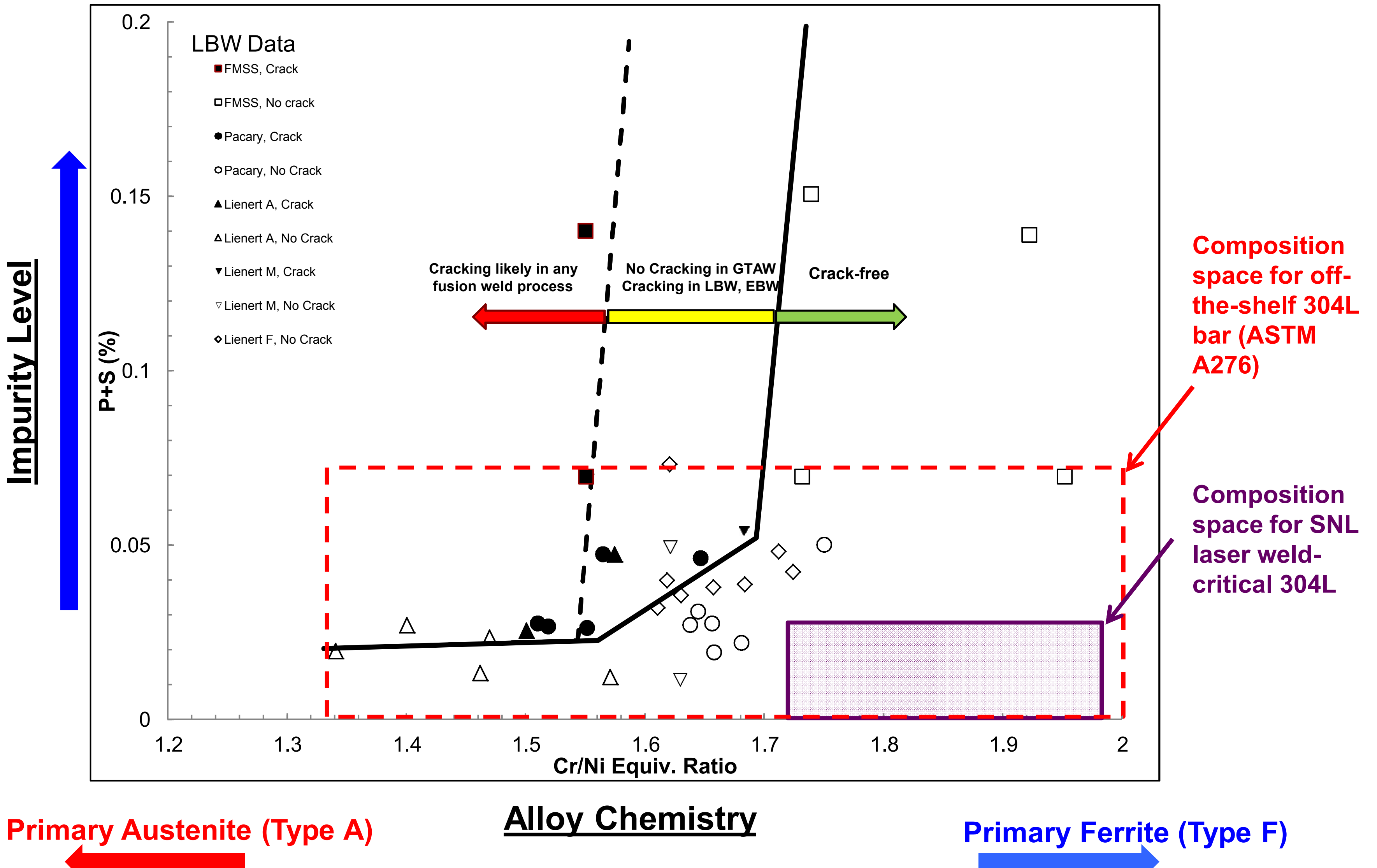
Alloy Chemistry: Increasing $(Cr/Ni)_{eq}$ →

Ferrite Promoters

Cr, Mo, Si, Nb, Ti

John C. Lippold, Damian J. Kotecki, Welding metallurgy and weldability of stainless steels, Wiley-Interscience, 2005, 357pgs

Relationship Between Stainless Steel Chemistry, Impurity Level, and Weld Crack Susceptibility



O. Hammar and U. Svennson, Solidification and Casting of Metals, Metal Society, London 1979. $(CrNi)_{eq}$ = [Cr+1.37(Mo)+1.5(Si)+2.0(Nb)+3.0(Ti)] / [Ni+0.31(Mn)+22(C)+14.2(N)+Cu]
Adapted from: J.A. Brooks, C.V. Robino, T.J. Headley, J.R. Michael. Welding Journal, 82(3):51s-64s. 2003.

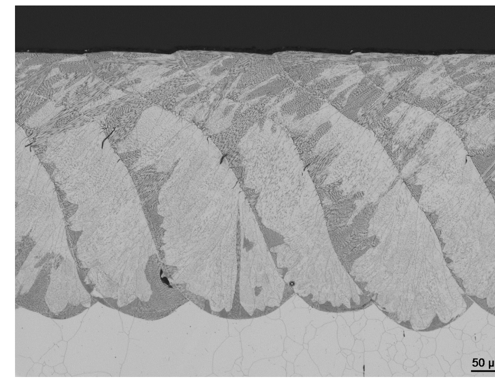
Motivation for investigating multiple melting/solidification behavior

- We often receive inquiries into rewelding limits for component reuse featuring autogenous welds
  - Technical basis for limits not well-established

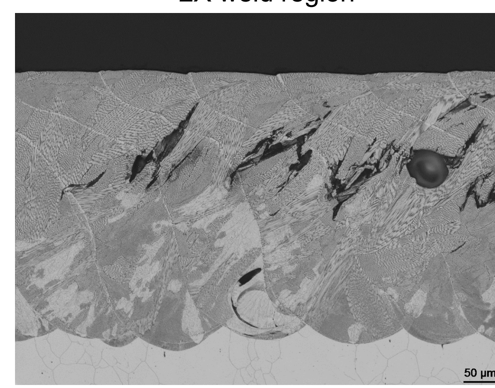
Laboratory Example

- A prototype enclosure assembly was to be joined using laser welding
- Housing and cover made from commercial vacuum arc remelted 304L (Low P+S, $(Cr/Ni)_{eq} = 1.73$)
- The small size and thermal constraints for this housing required laser pulsed seam welding
- Visual inspection of weld revealed hot cracks in weld termination overlap region
- The alloy had relatively low Mn content and this provided additional interest since VAR 304L producers often experience difficulty with Mn control

1X weld region



2X weld region



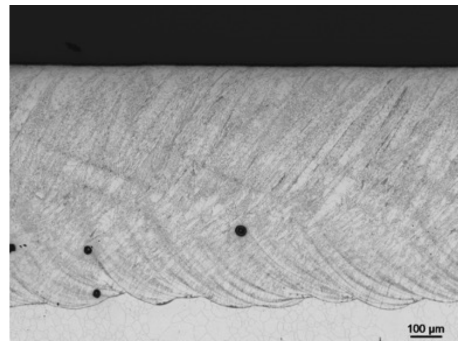
Multiple Melting/Solidification Events in Laser Welds

- Autogenous laser welding can impose a surprisingly high number of melting/solidification cycles on a given volume in a weld joint

- Closure welds have an overwelded termination
- Most welding specifications allow repair/rework welding
- Surveillance and reuse concepts can impose additional cycles
- Pulsed and cyclic seam welding add additional melting/solidification cycles compared to continuous wave
- Each cycle provides an opportunity for composition changes due to evaporation or impurity uptake

Termination overlap

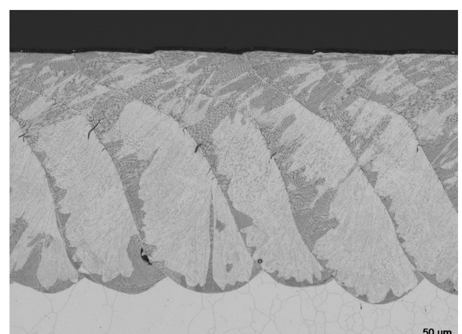
CW Seam



Weld Termination Region

$(2_{\text{termination overlap}})(3_{\text{rework/reweld}})(2_{\text{reuse}}) =$ 12 cycles

Pulsed Seam



$(3_{\text{pulse overlap}})(2_{\text{termination overlap}})(3_{\text{rework/reweld}})(2_{\text{reuse}}) =$ 36 cycles

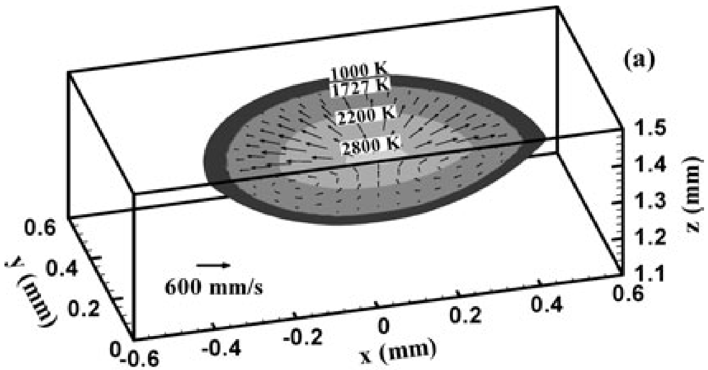
Alloying Element Evaporation

- Alloying element evaporation in laser welding is well known
- The phenomena is conceptually simple but is quantitatively extremely complex
- Primary factors include
  - Vapor pressure
  - Activity coefficient
  - Mass transfer coefficient
  - Surface temperature & gradient
  - Near surface gas composition
  - Surface condition and area

- Goal: to verify the phenomenology and establish practical working limits for a range of typical 304L compositions and typical laser welding process parameters

$$J_{ci} = K_{gi}\left(M_i \frac{a_i P_i^0}{R T_l} - C_i^b\right)$$

K_{gi} is the mass transfer coefficient of element i
M_i is the molecular weight of the element i
a_i is the activity of element i in the liquid metal
P_i^0 is the equilibrium vapour pressure of element i over its pure liquid
R is the gas constant
T_l is the temperature at the weld pool surface
C_i^b is the concentration of element i in the shielding gas



X He[1], T DebRoy[1] and P W Fuerschbach[2]
J. Phys. D: Appl. Phys. **36** (2003) 3079–3088

Materials & Processes

Three Alloys:

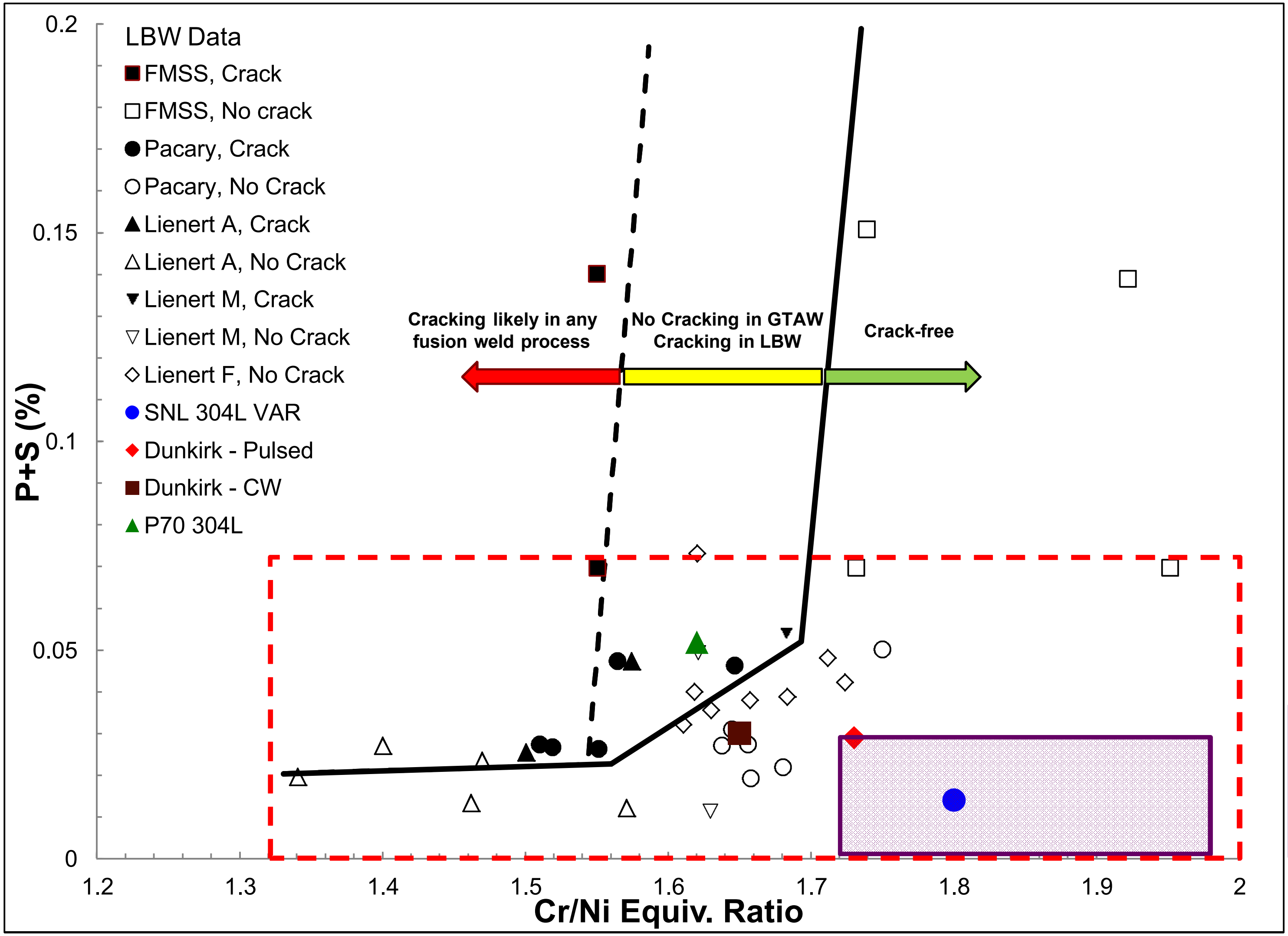
- SNL VAR 304L: controlled $(Cr/Ni)_{eq}$ and impurity level
- Dunkirk commercial VAR 304L: low Mn relative to our SNL practice
- Carpenter Project 70: commercial 304L, AOD resulfurized

Two Laser Seam Welding Procedures:

- Pulsed: 2.7 J/pulse @ 5 Hz; 1.5 ipm, ~525 W peak power, ~14 W avg.; 100 CFH co-axial Ar shielding
- CW 425 W, 80 IPM travel speed, 100 CFH co-axial Ar shielding

Element	SNL 304L VAR	Dunkirk G19780K04 (Pulsed Welds)	Dunkirk G21003K08 (CW Welds)	Project 70 304L
Cr	19.63	18.95	18.5	18.26
Mo	0.05	0.32	0.24	0.49
Si	0.67	0.48	0.37	0.62
Nb	NR	0.04	0.01	NR
V	0.04	NR	0.03	NR
W	NR	0.05	<0.05	NR
Ti	<0.01	<0.01	<0.01	NR
Ta	NR	NR	<0.01	NR
Al	0.01	<0.01	<0.01	NR
Ni	10.23	10.13	10.14	10.20
Mn	1.51	1.03	1.10	1.76
C	0.020	0.009	0.015	0.018
N	0.020	0.047	0.049	0.020
Co	0.02	0.12	0.08	NR
Cu	0.07	0.30	0.23	0.82
P	0.013	0.022	0.023	0.029
S	0.001	0.007	0.007	0.023
P+S	0.014	0.029	0.03	0.052
H&S Creq/Nieq	1.80	1.73	1.65	1.62

Evaluated Alloys: Solidification Crack Susceptibility



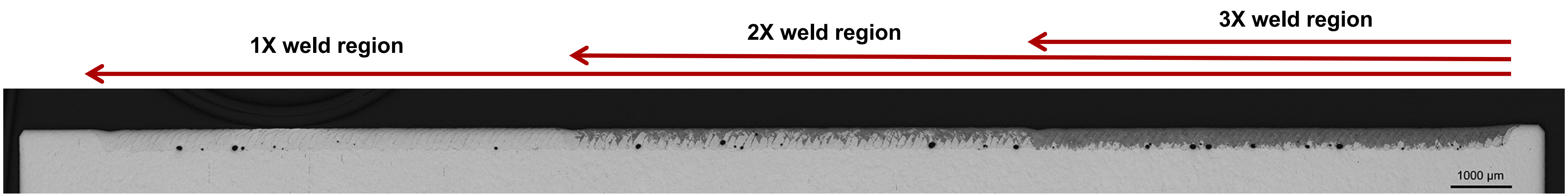
Composition space for off-the-shelf 304L bar (ASTM A276)

Composition space for SNL laser weld-critical 304L

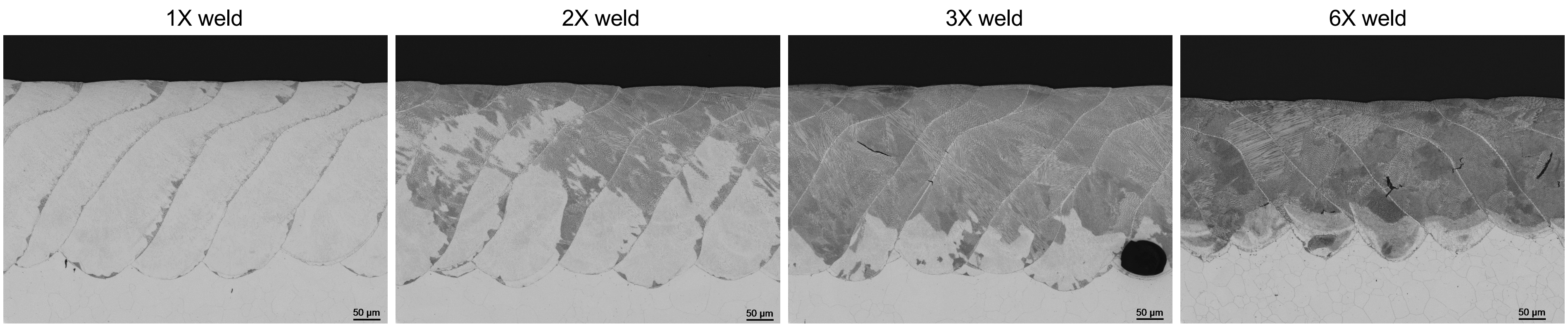
SNL VAR 304L – Pulsed

(initial $(Cr/Ni)_{eq}$: 1.80)

- No cracking until 3rd pass, moderate cracking with 6 weld passes
- Mode change with increasing passes, eventually reaching bottom of weld
- Reduced cracking severity compared with Dunkirk VAR (presumably due to higher starting Cr_{eq}/Ni_{eq} and S levels)



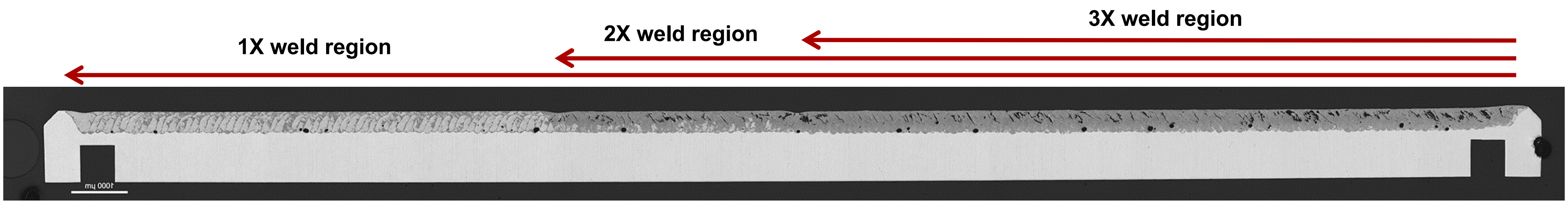
Optical micrograph montage of pulse seam weld – longitudinal section



Dunkirk Commercial VAR 304L – Pulsed

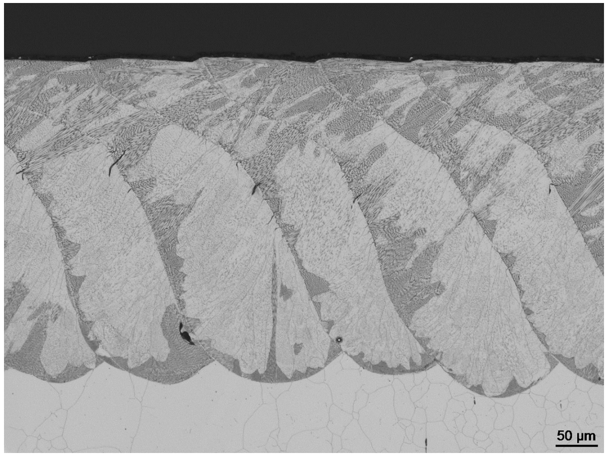
(initial $(Cr/Ni)_{eq}$: 1.73)

- Small amount of cracking even in first pass, largely FA solidification mode
- Increasing levels of AF solidification and cracking with increasing number of passes

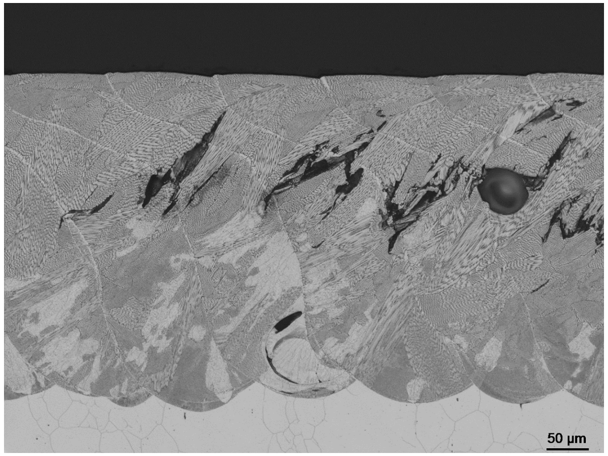


Optical micrograph montage of pulse seam weld – longitudinal section

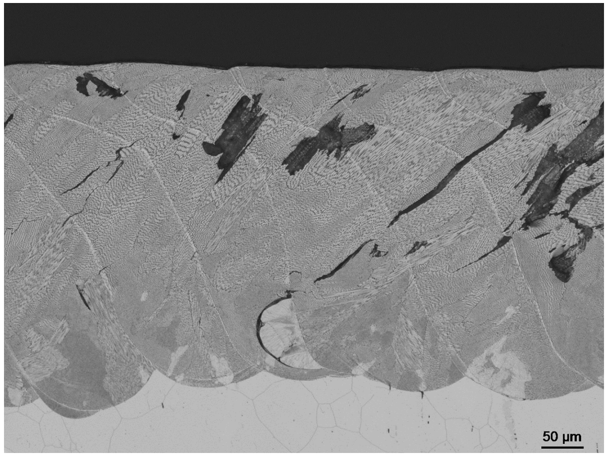
1X weld



2X weld



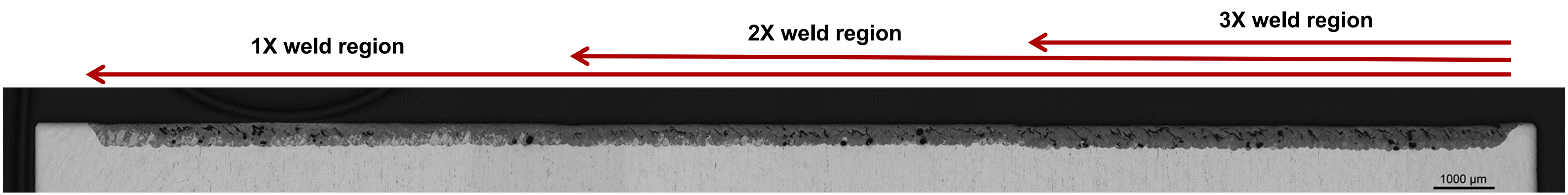
3X weld



Carpenter P70 304L: Pulsed

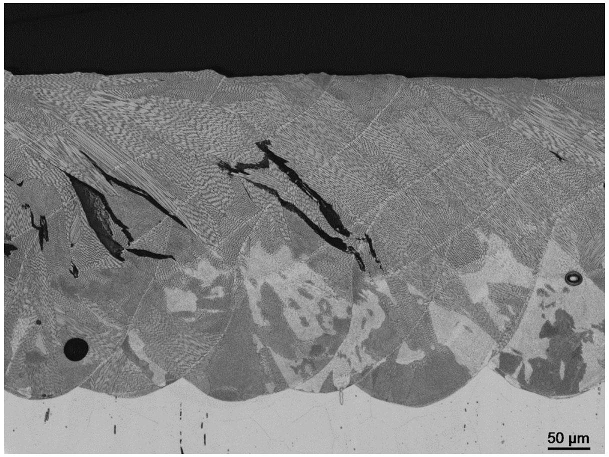
(initial $(Cr/Ni)_{eq}$: 1.62)

- A/FA solidification in initial pass - fully austenitic solidification thereafter
- Cracking observed for all welding conditions

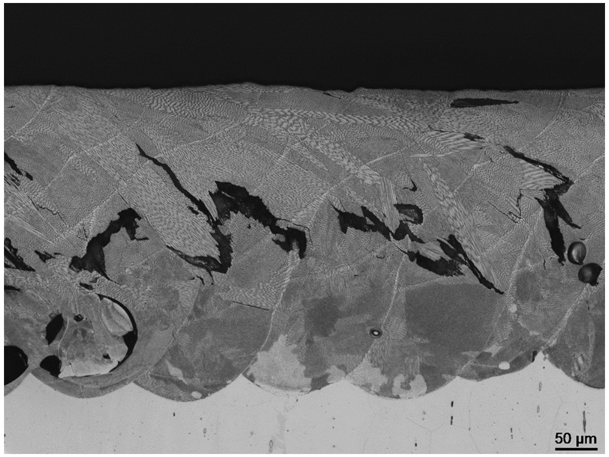


Optical micrograph montage of pulse seam weld – longitudinal section

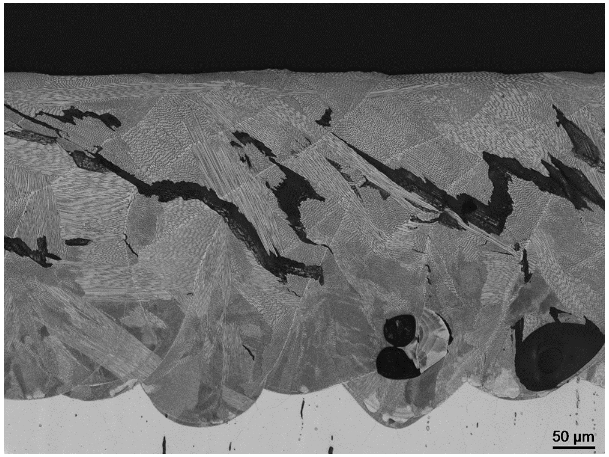
1X weld



2X weld



3X weld

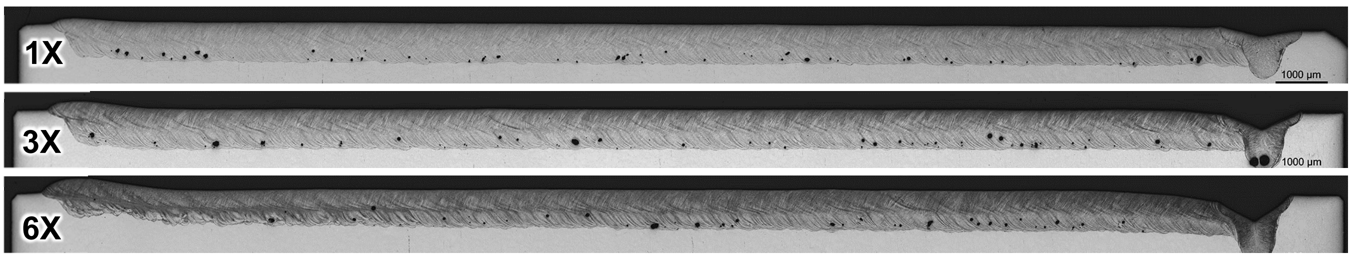


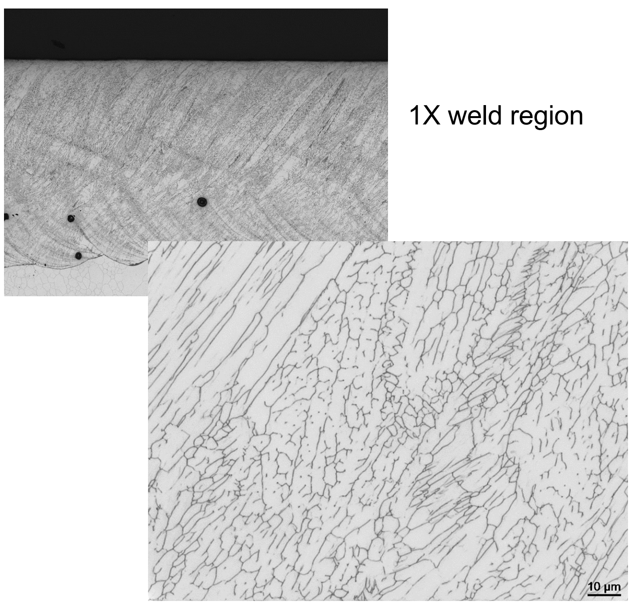
SNL VAR 304L - Continuous Wave

(initial $(Cr/Ni)_{eq}$: 1.80)

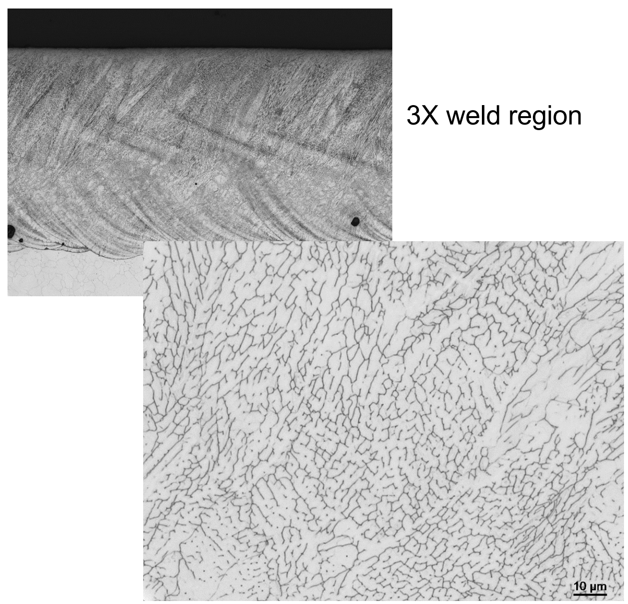
- All welds show primary ferrite (type FA) solidification
- No cracking up to 6X total weld passes

425 W
80 IPM
100 CFH Ar shielding

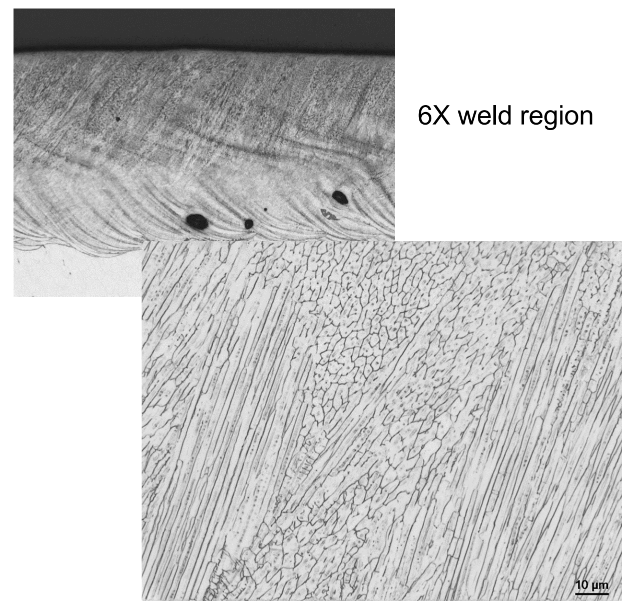




1X weld region



3X weld region



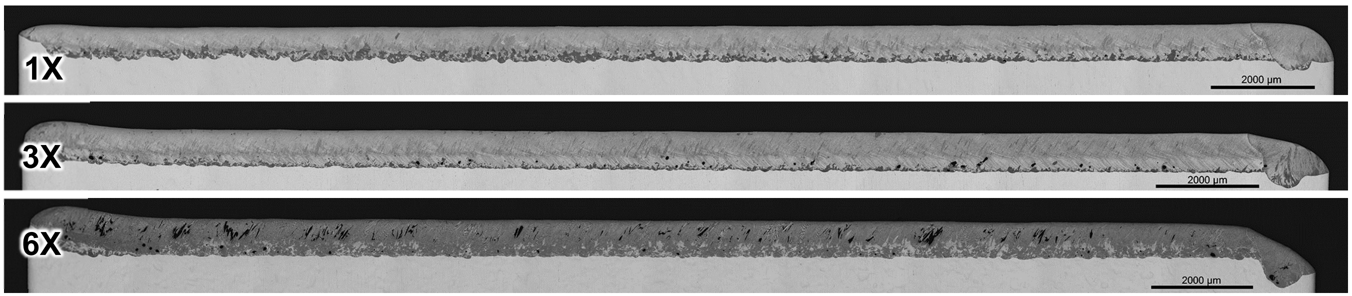
6X weld region

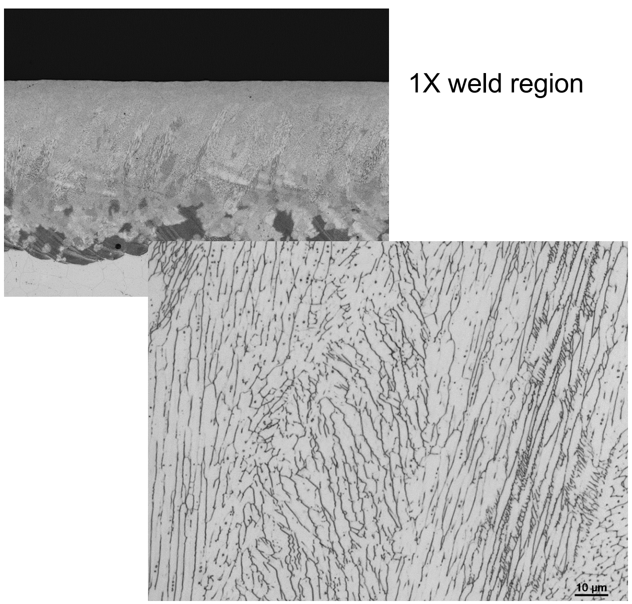
Dunkirk Commercial VAR 304L - Continuous Wave

(initial $(Cr/Ni)_{eq}$: 1.65)

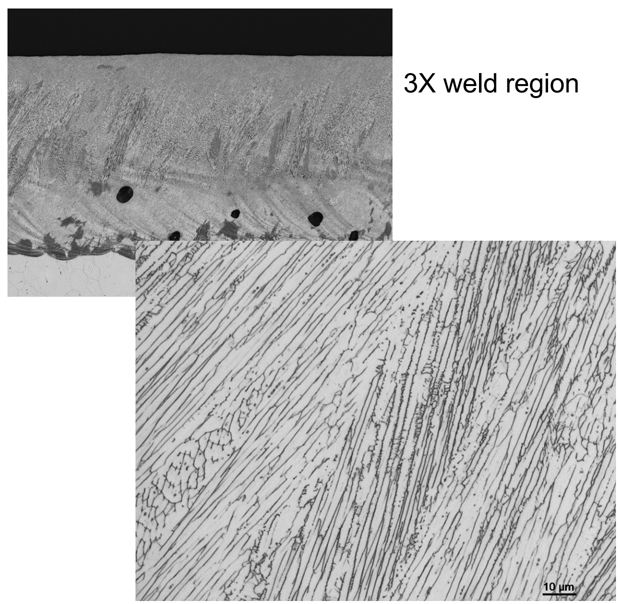
- Type FA solidification up to 3 passes, mixed mode A/FA solidification with 6X total welds
- No cracking up to 4X - cracking observed at 5X and above

425 W
80 IPM
100 CFH Ar shielding

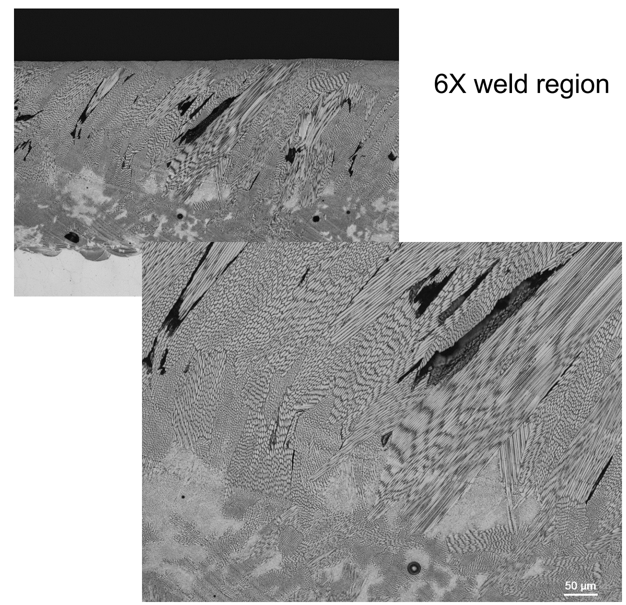




1X weld region



3X weld region



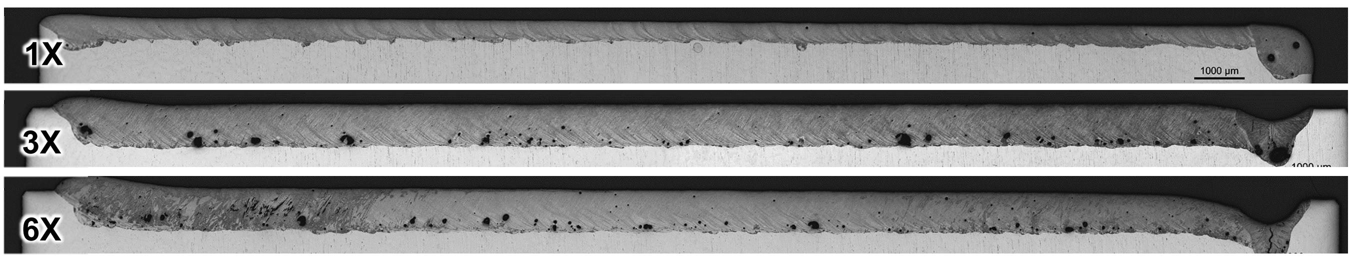
6X weld region

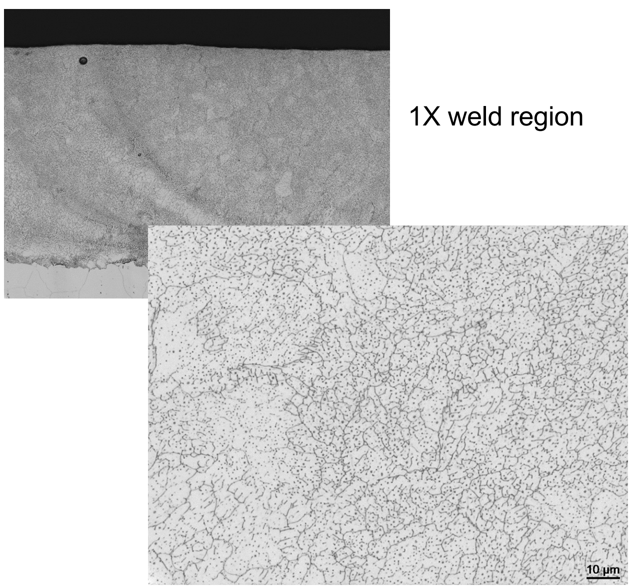
Carpenter P70 304L - Continuous Wave

(initial $(Cr/Ni)_{eq}$: 1.62)

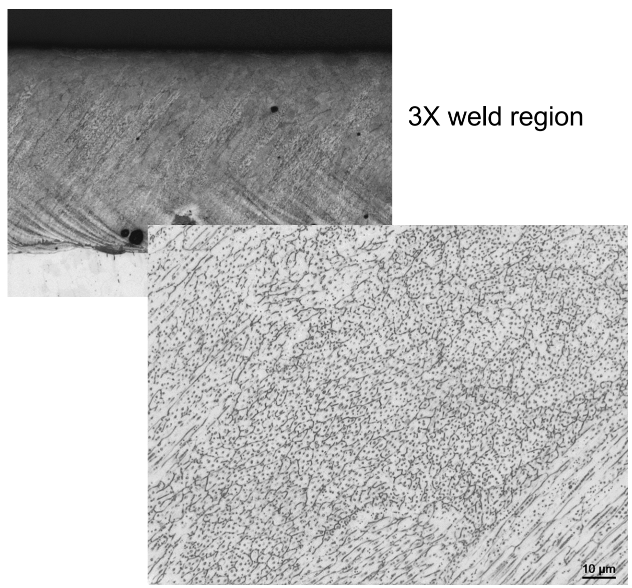
- Type FA solidification up to 3 passes, mixed mode A/FA solidification with 6X total welds - predominantly Type A near bar outer diameter
- No cracking up to 3X - cracking observed at 6X total welds

425 W
80 IPM
100 CFH Ar shielding

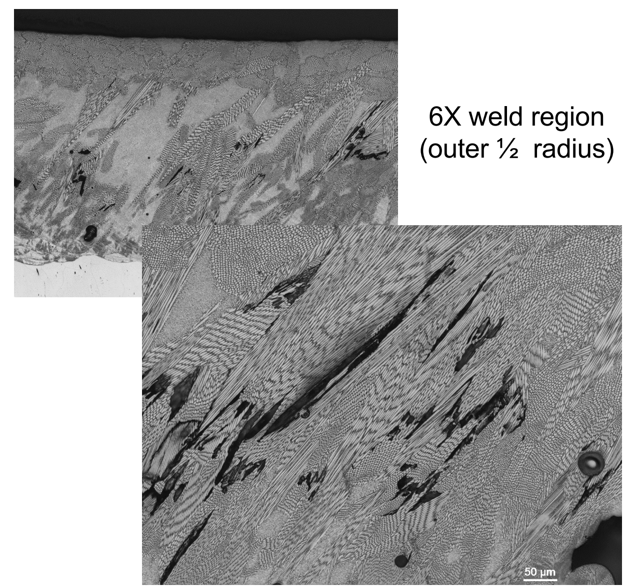




1X weld region



3X weld region

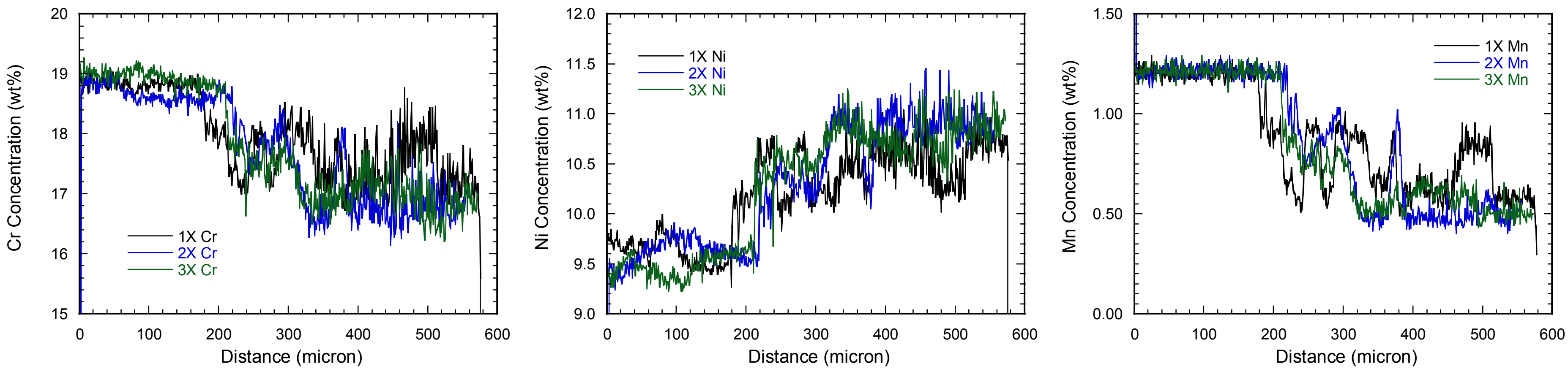


6X weld region (outer ½ radius)

Local Weld Metal Composition - Dunkirk

- Electron microprobe scans across base metal and welds
- Expected evaporation (decreases in Cr, Mn) and change in composition (increases in Ni) observed
- Mn can reach a very low concentration
- The data is difficult to interpret due to local variation, but does imply concentration gradients exist toward the surface
- A general tend toward increasing oxygen content was also observed

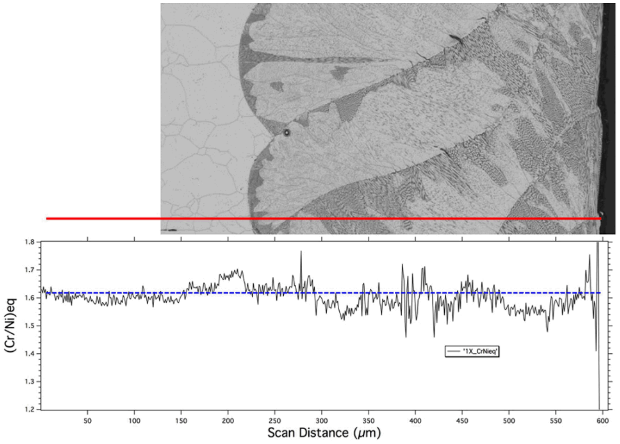
	Si	S	Mo	Cr	Mn	Fe	Ni	Cu	O
1X Base Metal Average	0.481	0.004	0.328	18.835	1.208	67.897	9.638	0.310	0.090
2X Base Metal Average	0.478	0.059	0.319	18.647	1.306	67.951	9.603	0.316	0.080
3X Base Metal Average	0.481	0.003	0.330	18.949	1.213	68.034	9.468	0.308	0.088
1X Weld Average	0.585	0.009	0.396	17.598	0.739	68.654	10.435	0.223	0.111
2X Weld Average	0.629	0.007	0.425	17.129	0.627	69.281	10.705	0.196	0.106
3X Weld Average	0.631	0.008	0.427	17.126	0.613	68.935	10.707	0.197	0.113



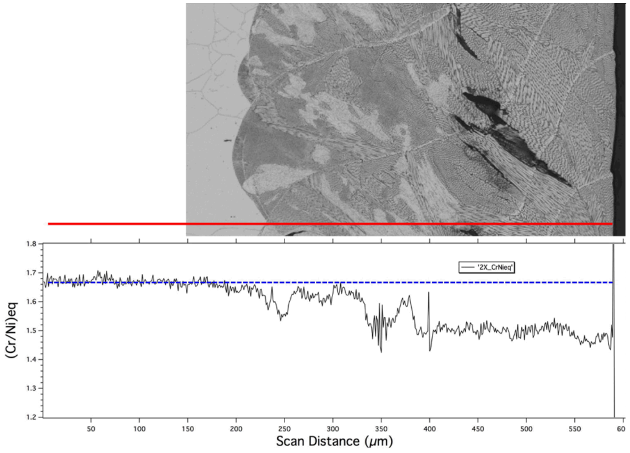
Weld Composition - Dunkirk Pulsed

- Conversion of the composition data to $(Cr/Ni)_{eq}$ provides a much clearer picture of the solidification behavior shifts on subsequent weld passes
- General monotonic decrease in $(Cr/Ni)_{eq}$ with increasing passes
- Supports the evaporation mechanism as primary change on rewelding

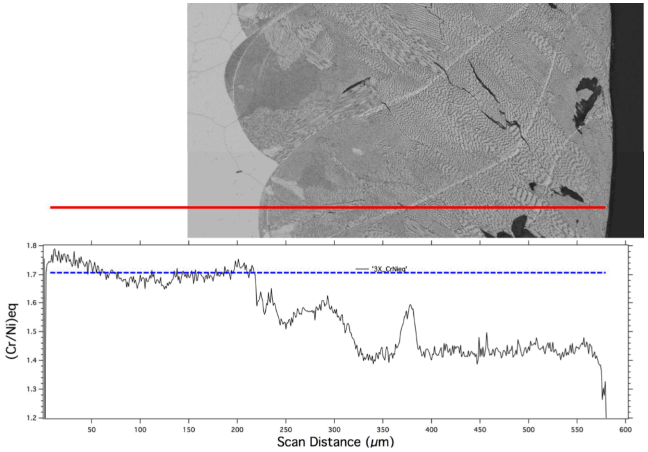
1X weld



2X weld



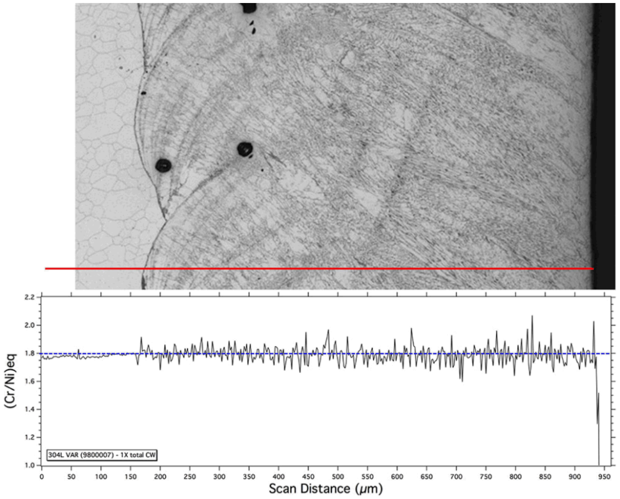
3X weld



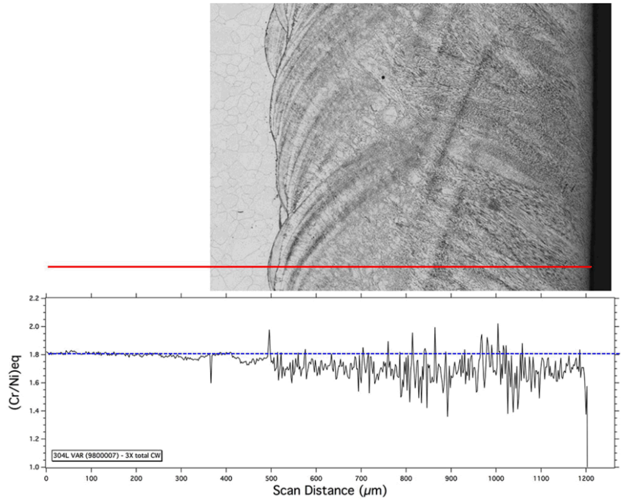
Weld Composition – SNL 304L VAR Continuous Wave

- General monotonic decrease in Cr_{eq}/Ni_{eq} with increasing passes, but much less severe than pulsed welding
- Supports the evaporation mechanism as primary change on rewelding

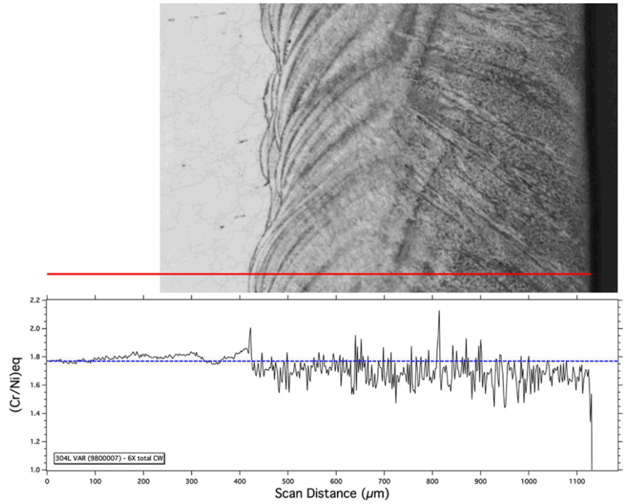
1X weld



3X weld



6X weld



Summary

- Evaporation during rewelding can significantly alter composition
- The changes in composition have a dramatic and progressive effect on solidification mode and cracking tendency
- As expected, due to the additional melting cycles and likely higher peak temperatures, pulsed weld schedules are more sensitive to the number of weld passes
- $(Cr/Ni)_{eq}$ ratios that are normally considered safe for pulsed welding (from single pulse tests) can be very sensitive to reweld cycles

Alloy	Number of Welds - Pulsed				Number of Welds - Continuous Wave			
	1	2	3	6	1	2	3	6
9800007	0	75/25	25/75	100	0	0	0	0
Dunkirk	75/25	25/75	100	NE	0	0	0	100
P70	25/75	100	100	NE	0	0	0	0* / 100*

* variable across bar diameter

0	Fully FA
75/25	Mostly FA
25/75	Mostly AF
100	Fully AF

Alloy	Number of Welds - Pulsed				Number of Welds - Continuous Wave			
	1	2	3	6	1	2	3	6
9800007	0	0	1	2	0	0	0	0
Dunkirk	1	3	3	NE	0	0	0	3*
P70	3	3	3	NE	0	0	0	3*

* variable across bar diameter

0	No Cracking
1	Minimal Cracking
2	Moderate Cracking
3	Severe Cracking