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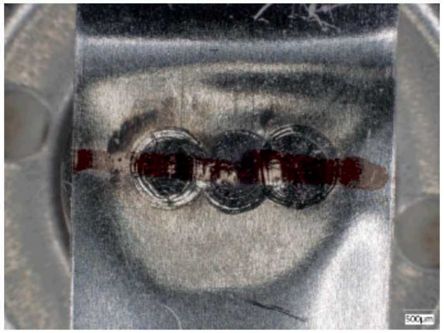

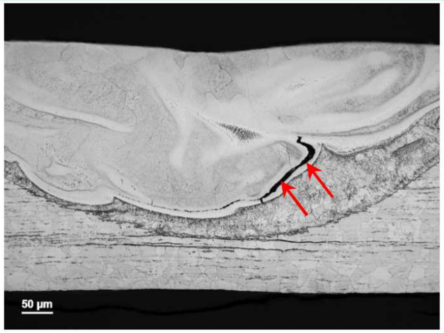

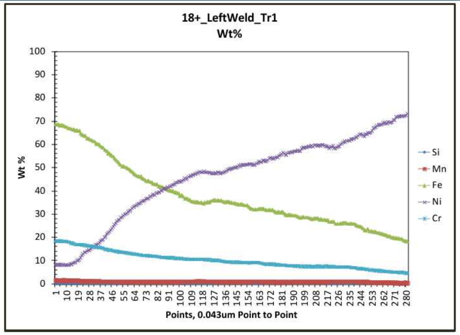

Laser Welding of Multi-Cell Battery Packs

Don Susan, Dan Tung, Pierrette Gorman, Jeff Rodelas, Christina Profazi,

Dick Grant, and Huan Pham

AWS Meeting, Atlanta, GA November 7, 2018

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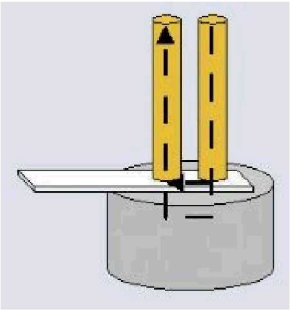
Background & Motivation

- Battery packs, similar to those in household power tools, historically joined by soldering or resistance welding (parallel gap)

Resistance-welded battery pack assembly

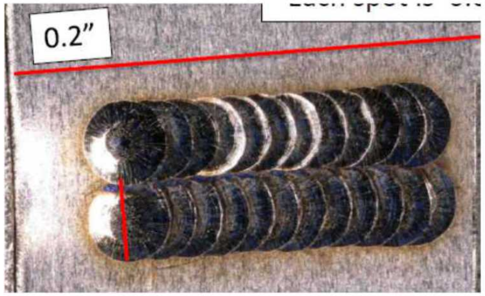


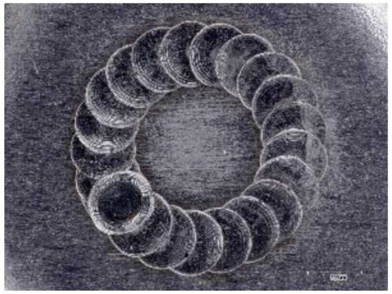
Soldered battery pack assembly

- Why investigate laser welding?
  - Requirements for higher strength than soldering can provide.
  - Supplier and in-house existing capabilities in laser welding
  - Searching for more consistency, *faster manufacturing cycles* than resistance welding. In addition, laser welding gives the ability to produce more welds (more total welded area) in a small footprint -- higher overall joint strength.

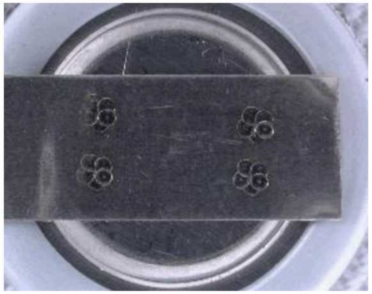
Laser Welding of Battery Packs

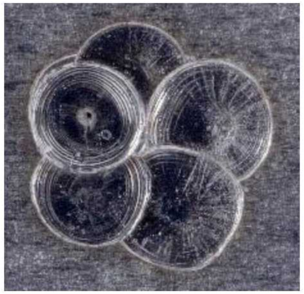
- Pros
  - Supplier and in-house existing capabilities in laser welding
  - *faster manufacturing cycles*
  - Ability to produce more welds (more total welded area) in a small footprint -- higher overall joint strength.
  - High pull strength
  - Flexibility in design of overlapping spots





- Cons
  - Fixturing complexity
  - Difficult to produce solid-state welds (laser braze)
  - Major concern about breach of the battery terminal and release of electrolyte fluid. *Therefore, weld penetration depths/weld widths must be large for high strength, but shallow enough for margin for breach.*





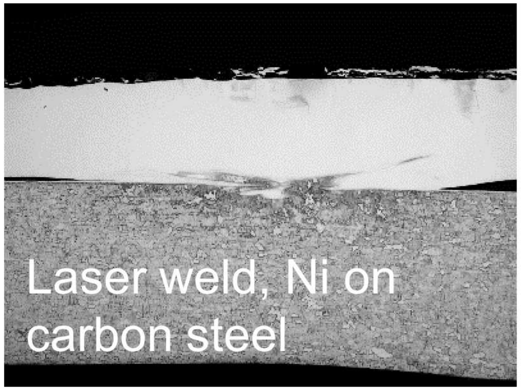
Design wide, but shallow, conduction mode laser welds.

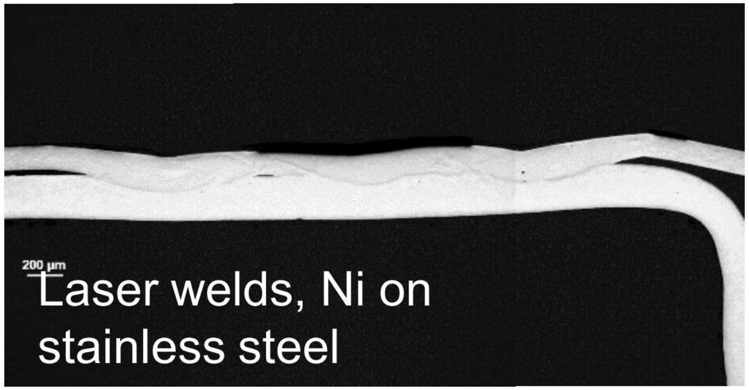
Piercing lap, dissimilar welds.

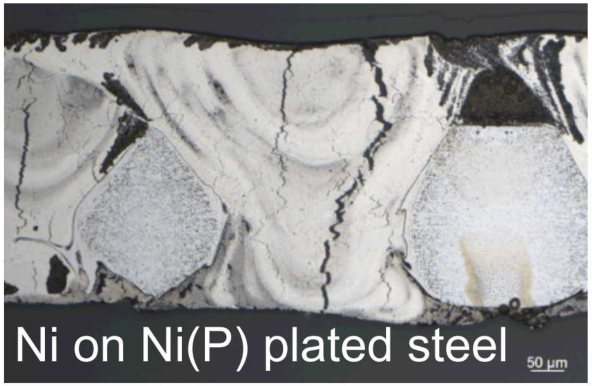
Variety of battery terminal materials

- The materials of construction of commercial cells is controlled by the major manufacturers, making batteries by the millions
- Three different terminal materials encountered:
  - Carbon steel
  - Stainless steel
  - Electroless Ni(P) plated carbon steel
- Tab strip material is Ni200
- Joining process must be flexible enough to handle whatever material the supplier happens to provide

5 mil thick Ni strip





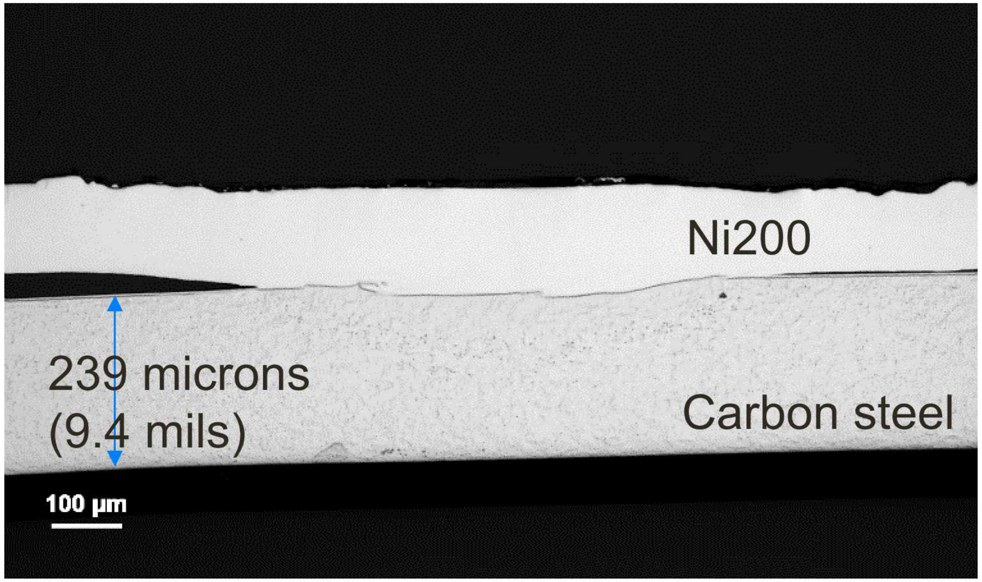


Laser Welding of Battery Packs

- General laser welding parameters
  - 10 – 30 msec pulse duration
  - 690W – 1.9 kW
  - 1.2 mm beam diameter
  - Overlapping spots

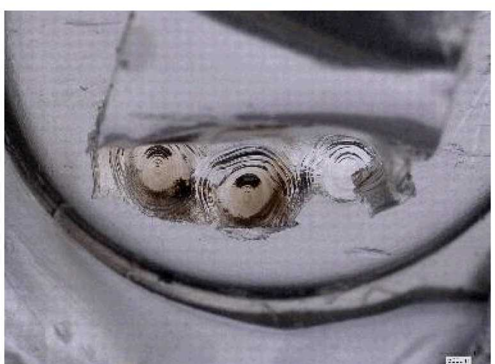
- As shown on the following slides, robust laser welding parameters can be developed, with target weld penetration depths, just like any other weld process development.

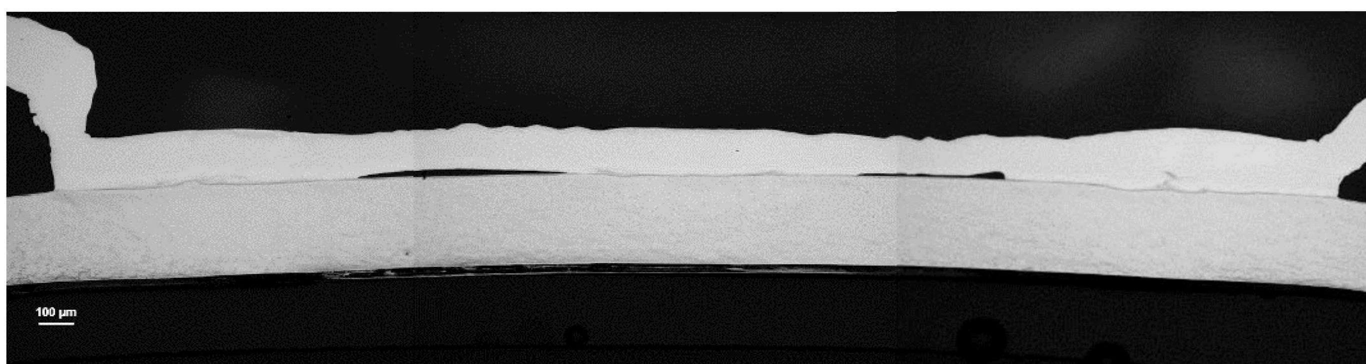
Initial Laser Welding Trials



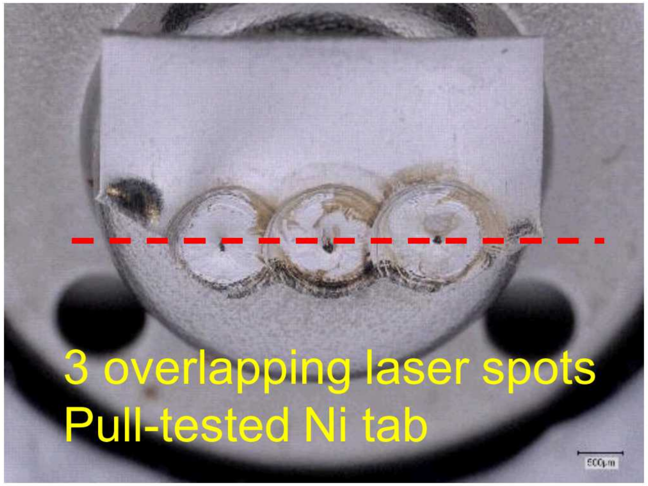
Initial laser welding trials produced shallow welds (< 1 mil penetration depth into substrate). Even so, pull strengths were adequate in many cases because overall weld area, not penetration depth is important. *Similar to a laser braze; melt one material, but not the other.* However, deeper penetration depth desired for process margin…

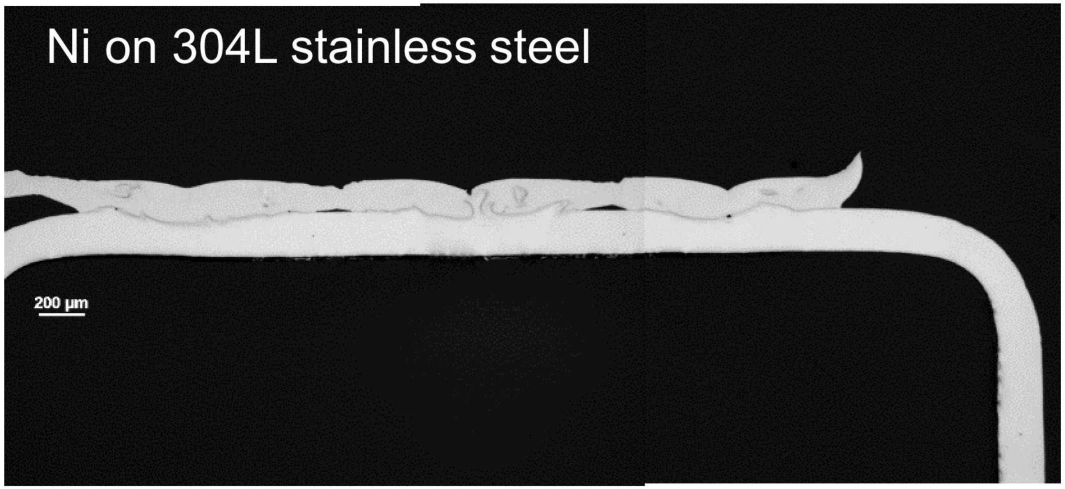
Caution: Overlapping spot welds viewed from above, may contain significant gaps between each weld





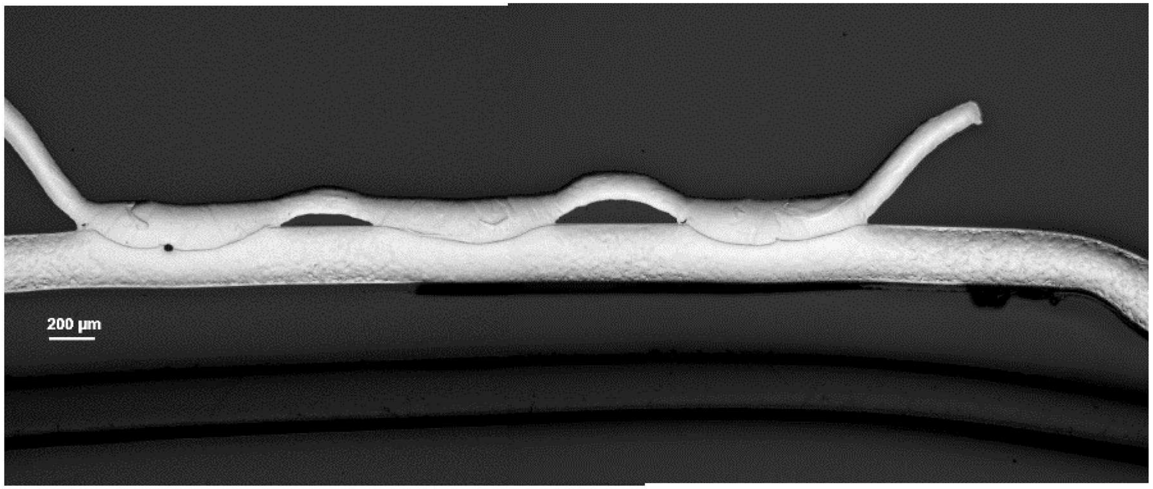
Development of Deeper Welds



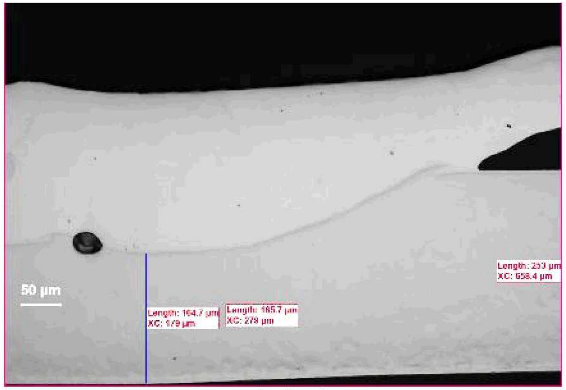


- Average weld penetration is ~1.53 mils (38.8 microns)
- Small triangular shaped voids between the welds
- Weld interface is undulating (not smooth), evidence for mixing

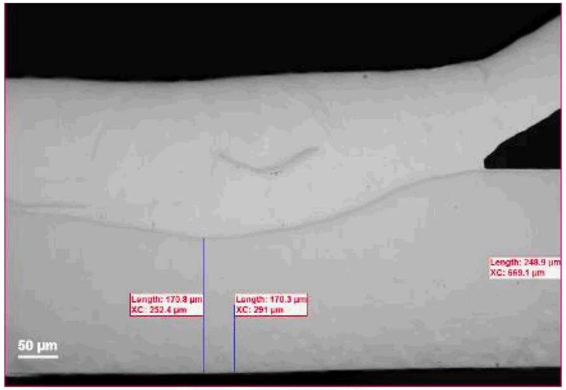
Development of Deeper Laser Welds



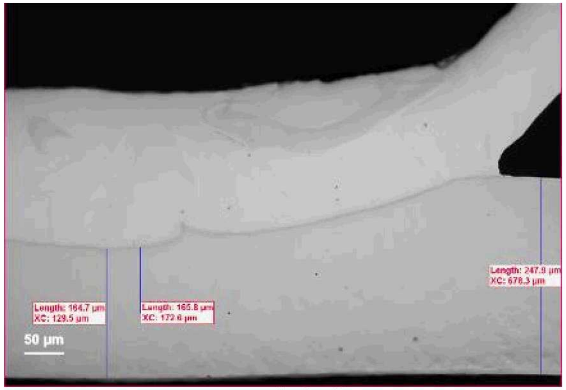
- Electrode material is ~10 mils thick (~250 microns)
- Average weld penetration is ~3.3 mils (84 microns)
- More rounded weld profile and undulating Ni foil between welds



weld 1

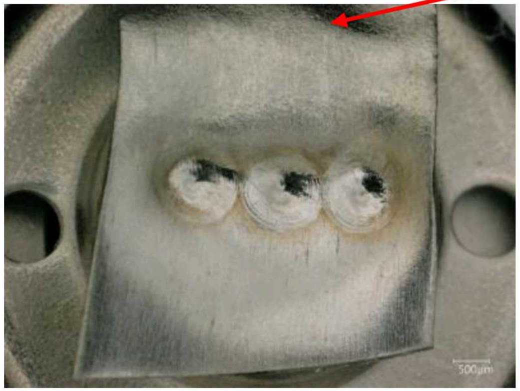


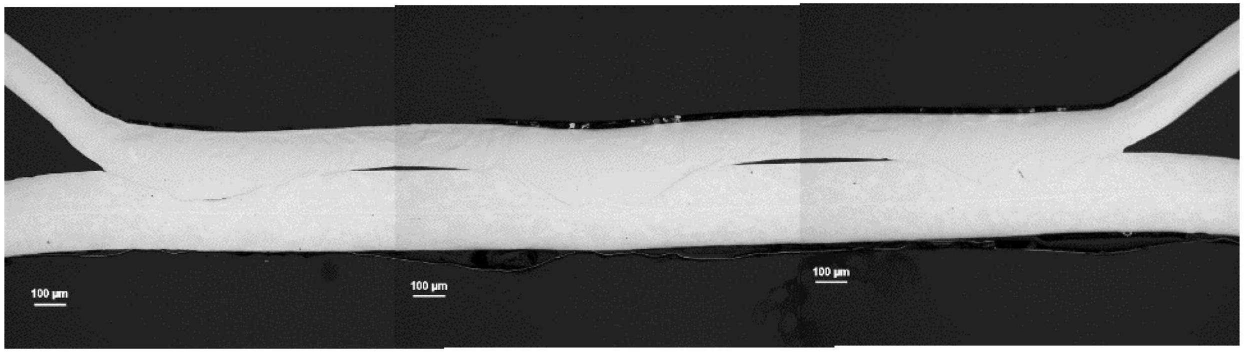
weld 2



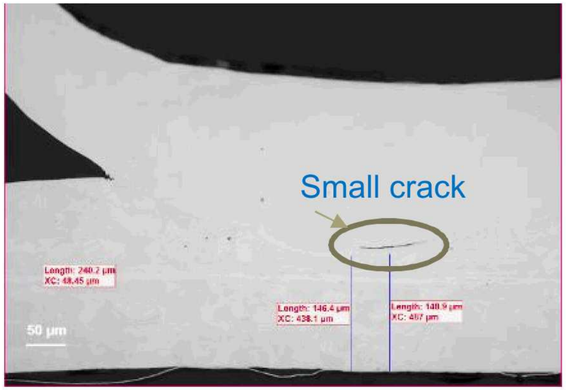
weld 3

Fractured in the nickel strip, away from welds

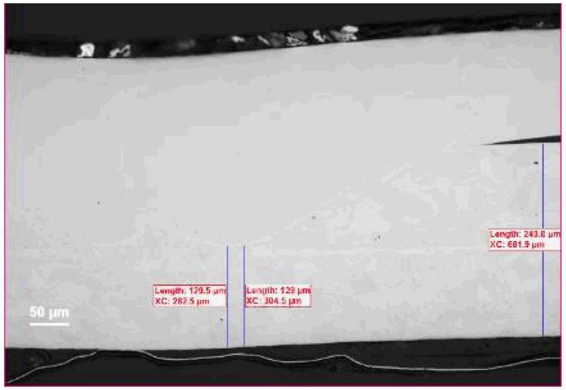




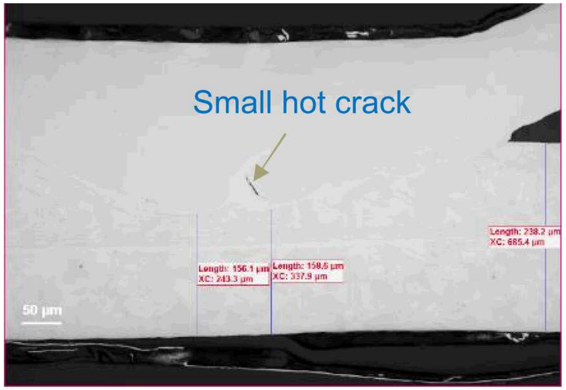
- Welds appear close together in “top down” view, cross-section shows small gaps
- Average weld penetration is deeper on the positive terminals: ~3.8 mils (97 microns)
- Weld shape indicates beginning of transition from conduction mode to keyhole mode



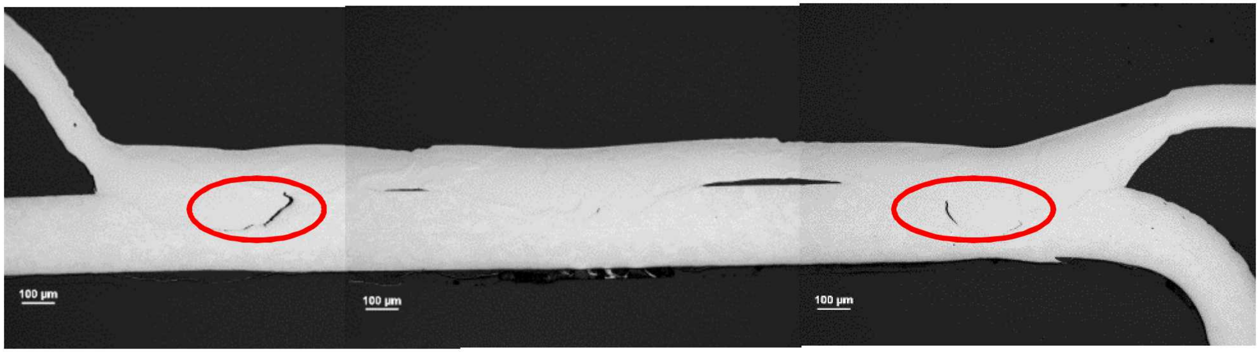
weld 1



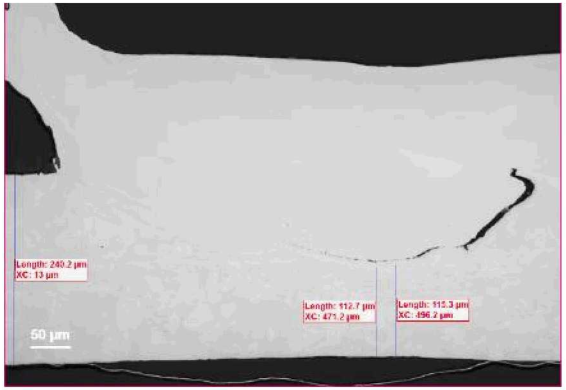
weld 2



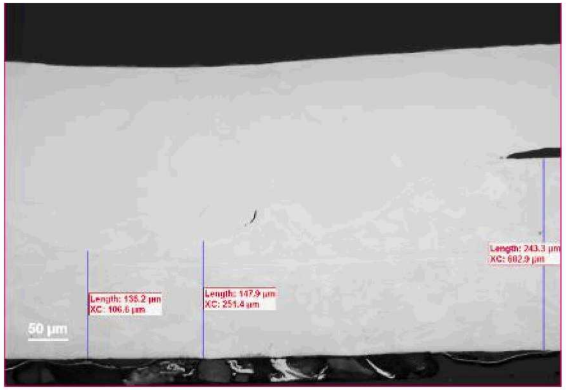
weld 3



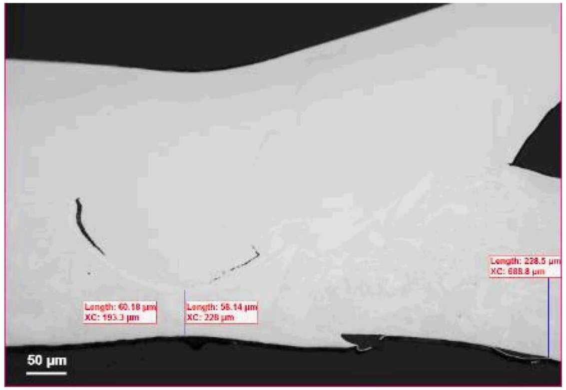
- Fairly deep pentration: 4.2 – 6.7 mils (107 – 170 microns)
- Strange cracks begin to appear. The shape and orientation of the cracks does not appear like traditional hot cracking. Cracks do not affect pull strength.
- Weld shape indicates transition to keyhole mode welds



weld 1

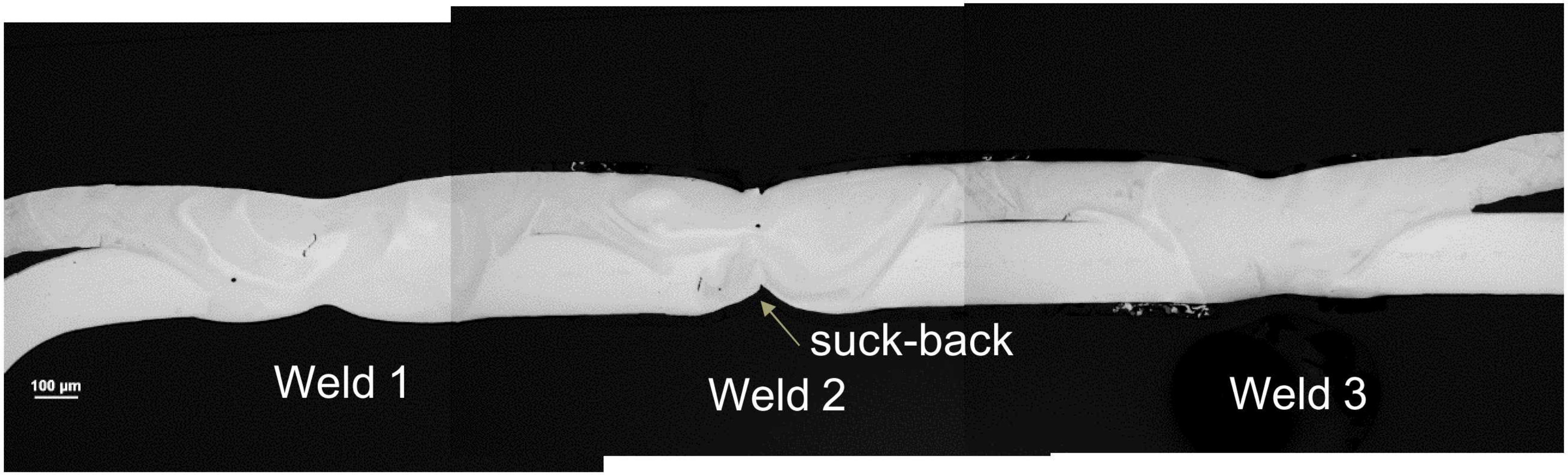


weld 2

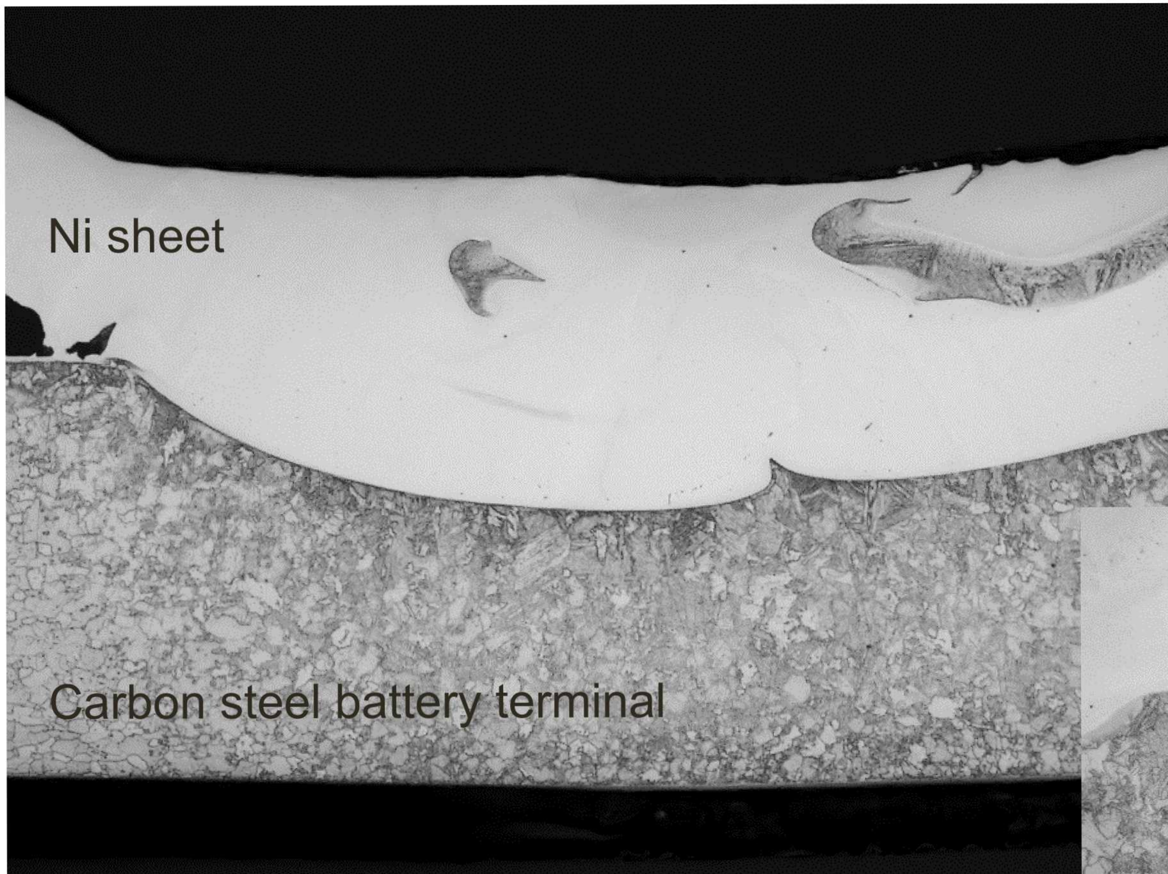


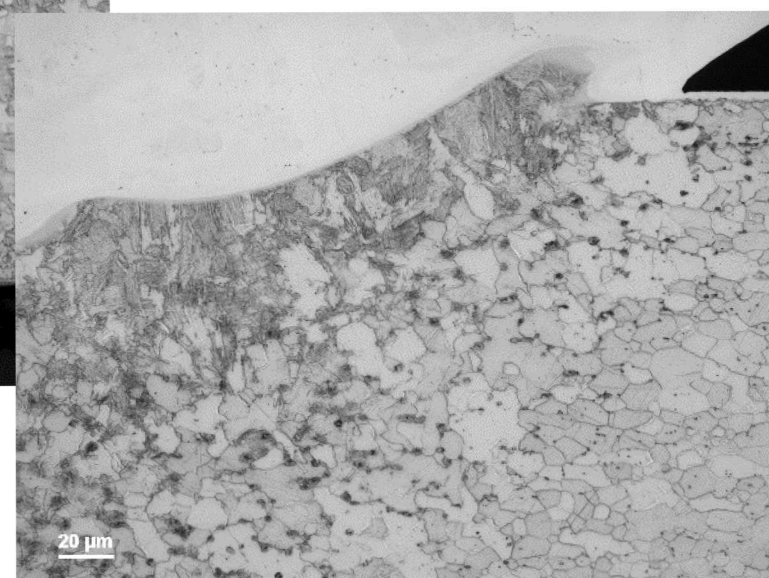
weld 3

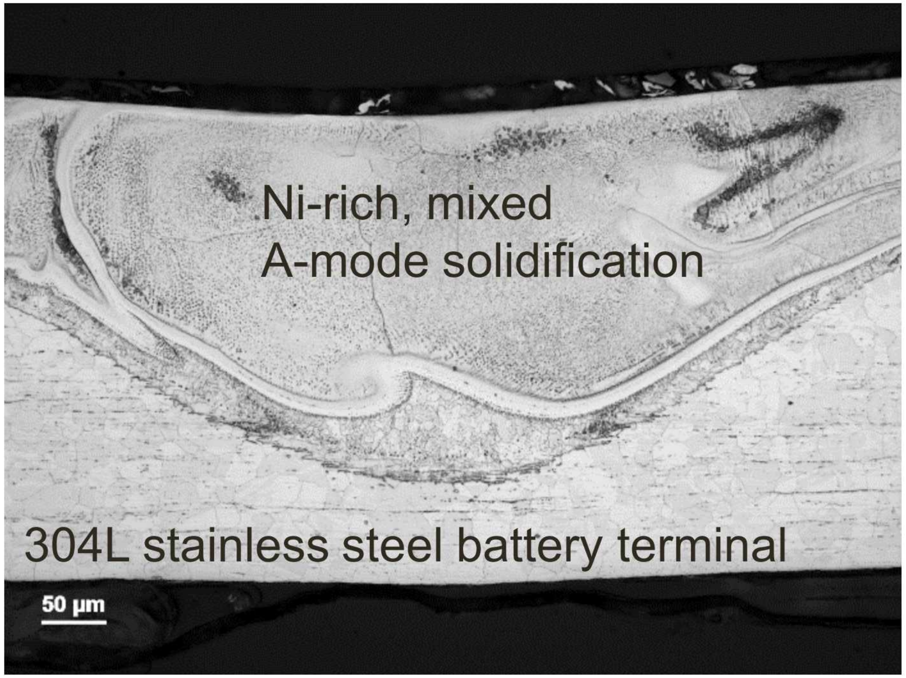
- Welds are full-penetration. Small hot cracks are present.
- Weld 2 shows significant “suck-back”. Unsupported liquid melt pool sucks back due to surface tension effects. Danger of drop-through and breach.

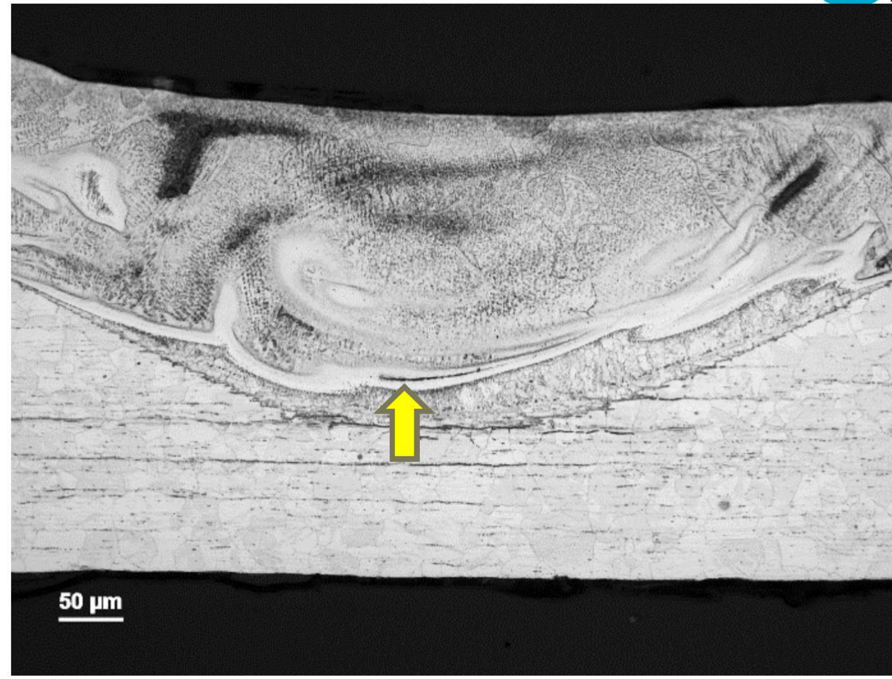


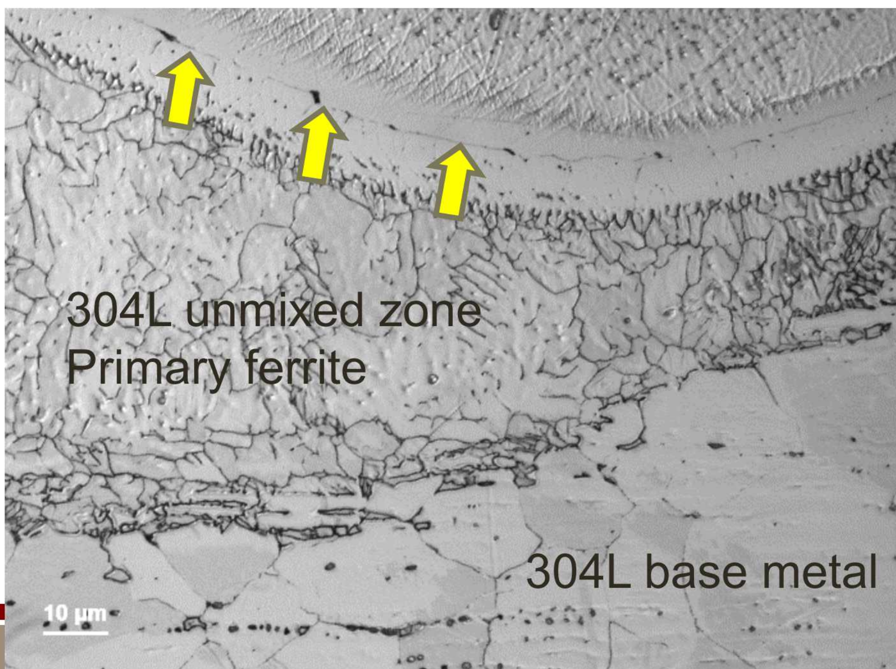
Observation in Etched Condition

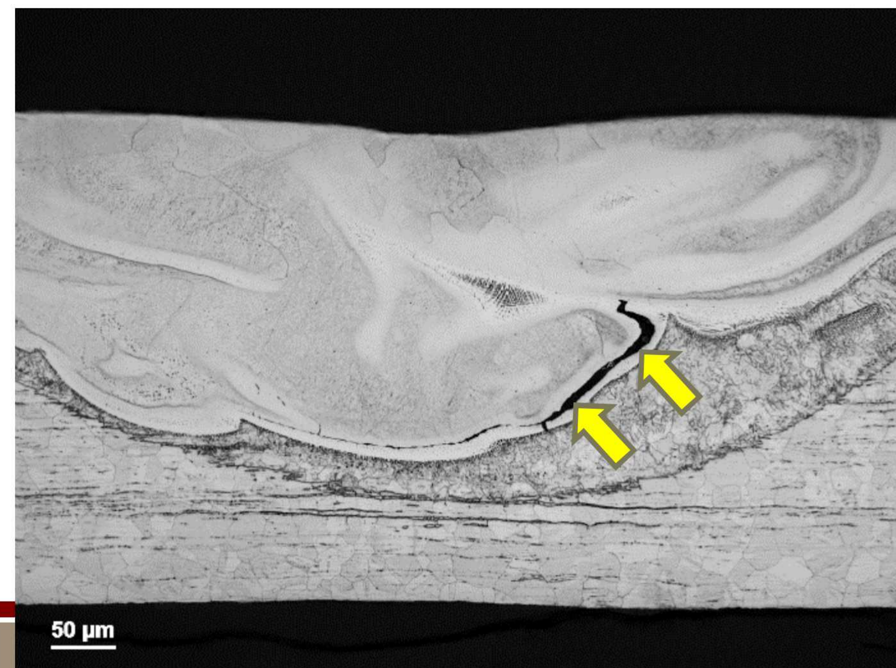




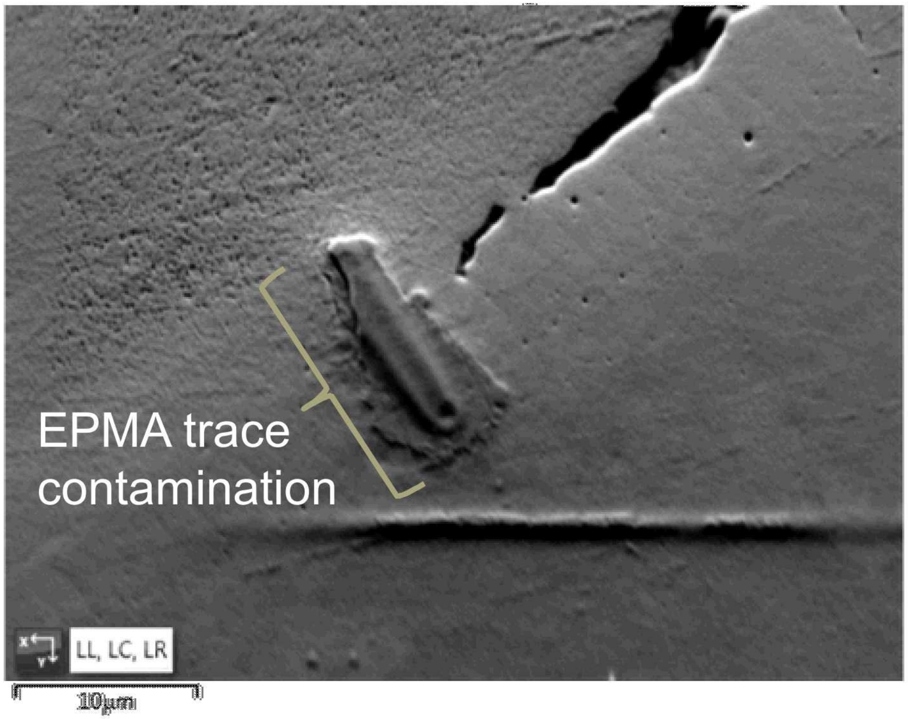

Ni-rich, mixed
A-mode solidification
304L stainless steel battery terminal
50 µm


50 µm

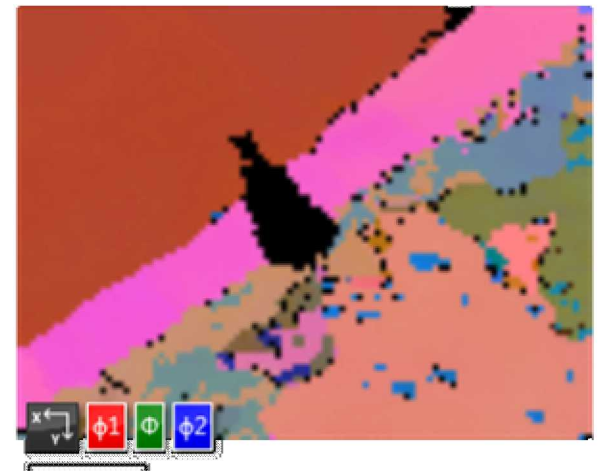

304L unmixed zone
Primary ferrite
304L base metal
10 µm


50 µm

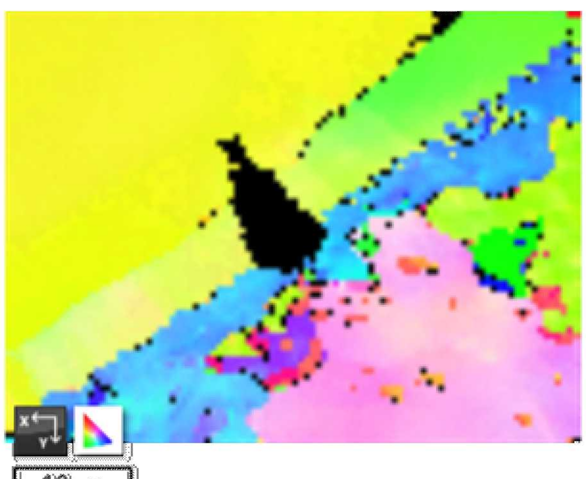
EBSD shows large interfacial grain along the boundary between unmixed and mixed zone



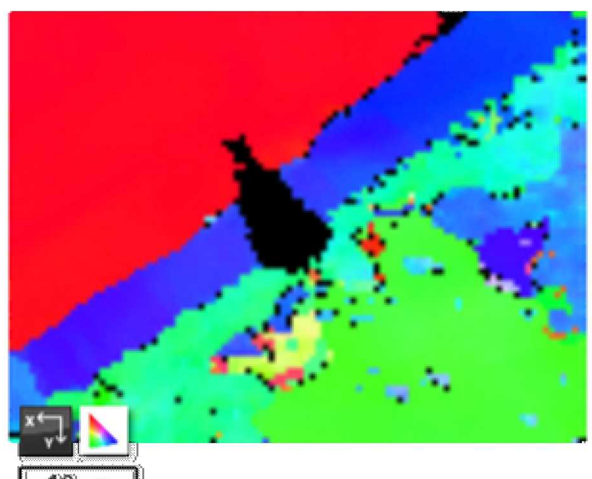
Euler Color 3



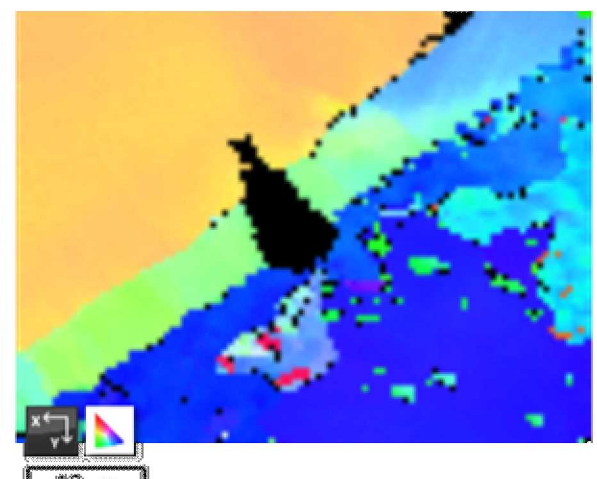
IPF X Color 3



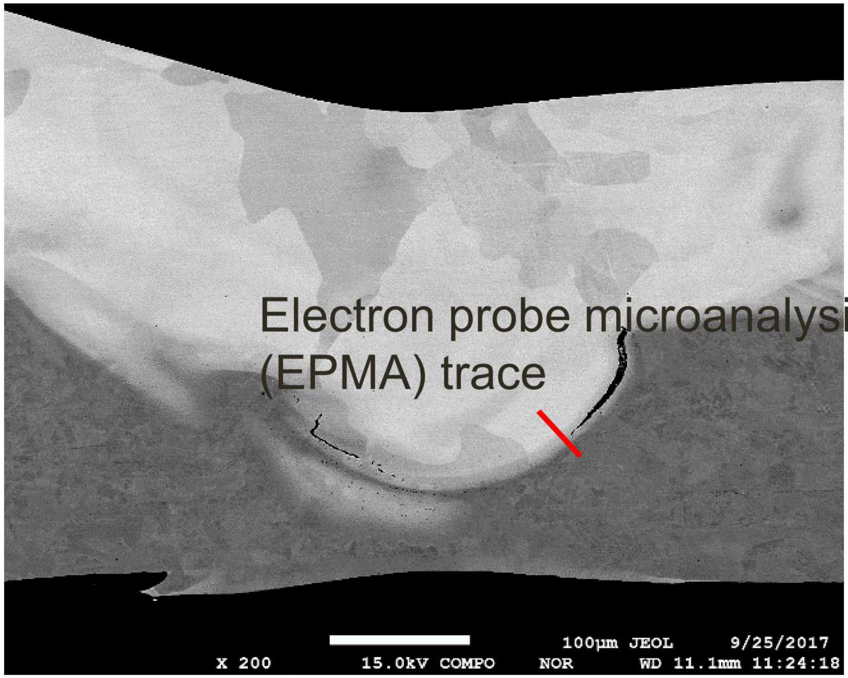
IPF Y Color 3

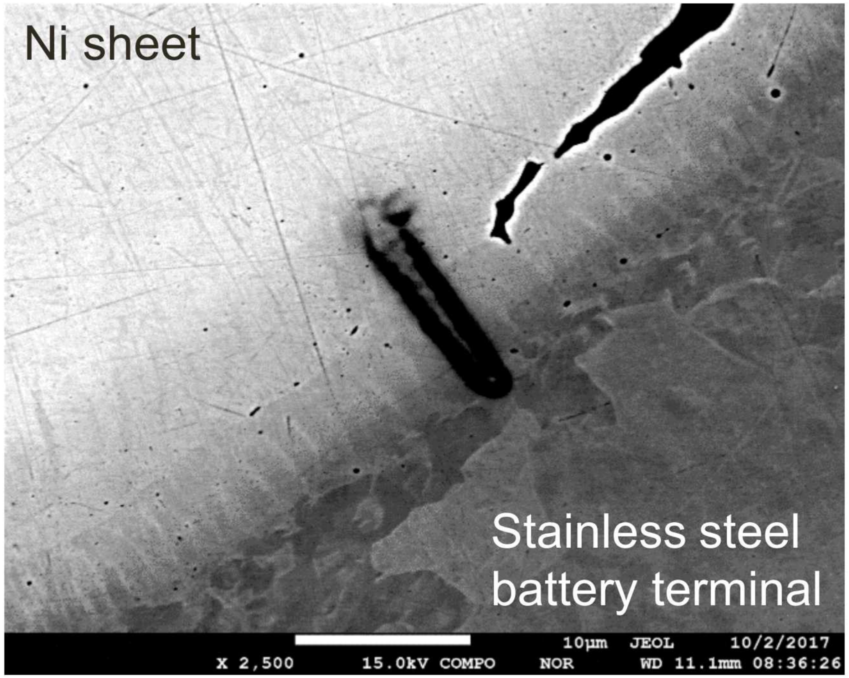


IPF Z Color 3



Electron Probe Microanalysis (WDS)



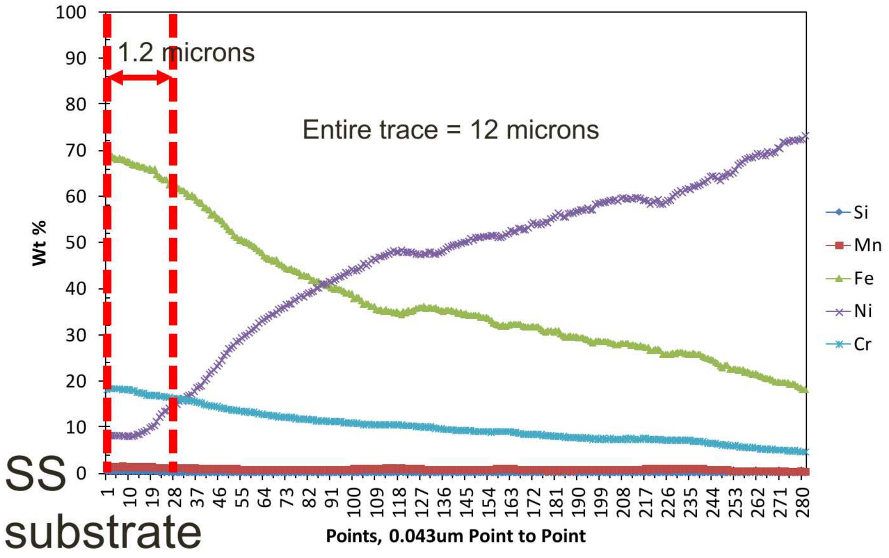


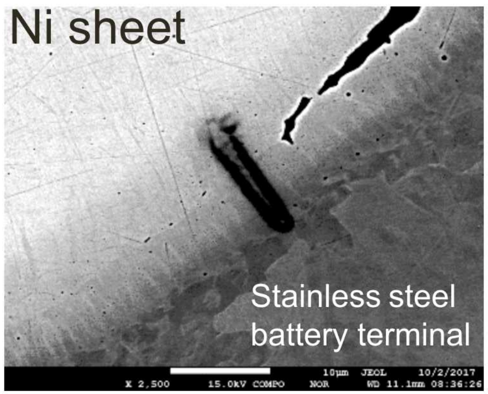
- Electron probe microanalysis (EPMA) used to determine composition change across the region where cracks form.
- In cracked region, dramatic composition change in short distance ~ 12 microns

	Fe	Cr	Ni	Mn	Si	Cr_{eq}	Ni_{eq}	Cr_{eq}/Ni_{eq}
Point 1	70.768	18.716	8.537	1.626	0.352	18.72	8.54	2.19
Point 28	65.822	17.171	15.458	1.272	0.277	17.17	15.46	1.11

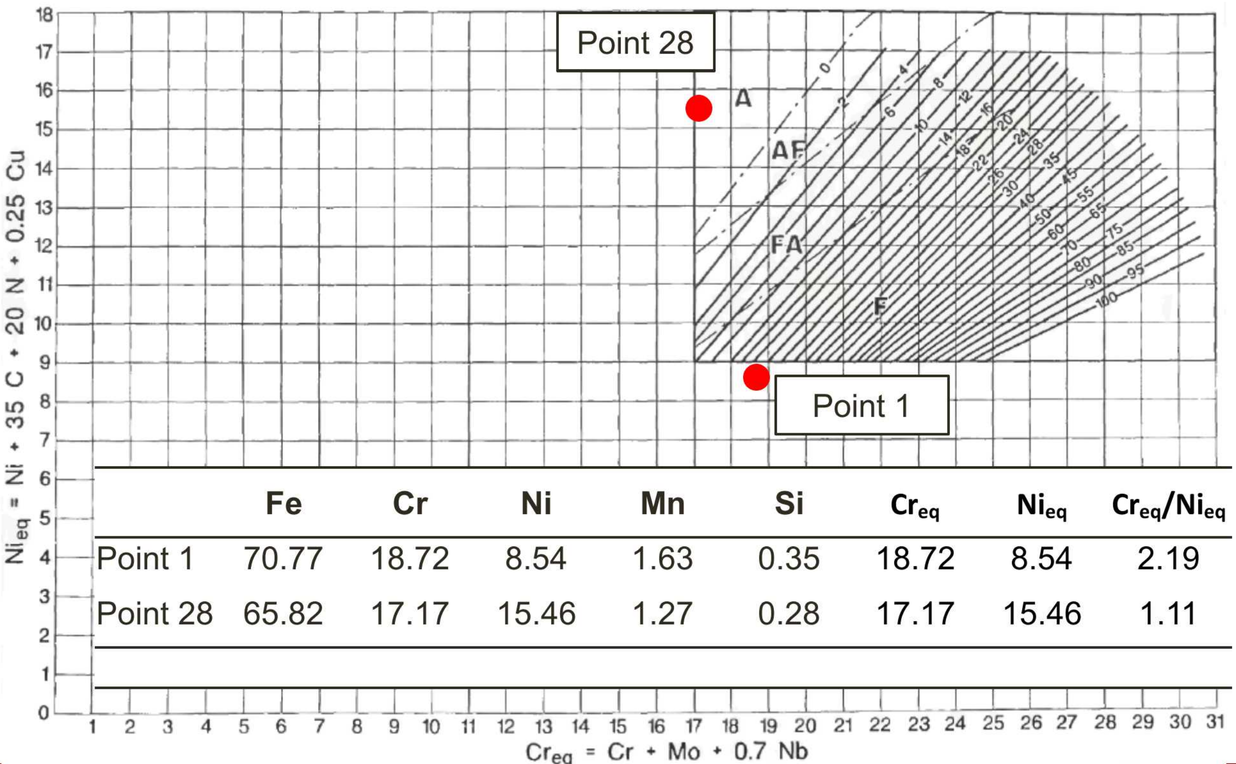
*Mo, Nb, Cu may not be present.

Electron Probe Microanalysis (EPMA) and WRC-1992 Diagram



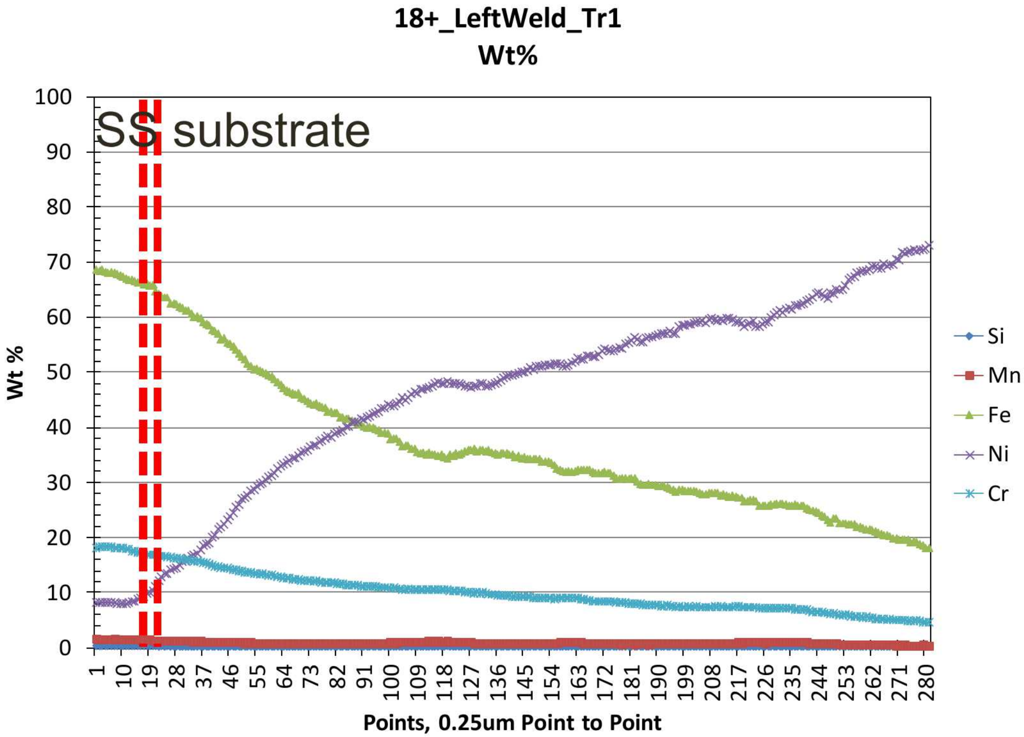


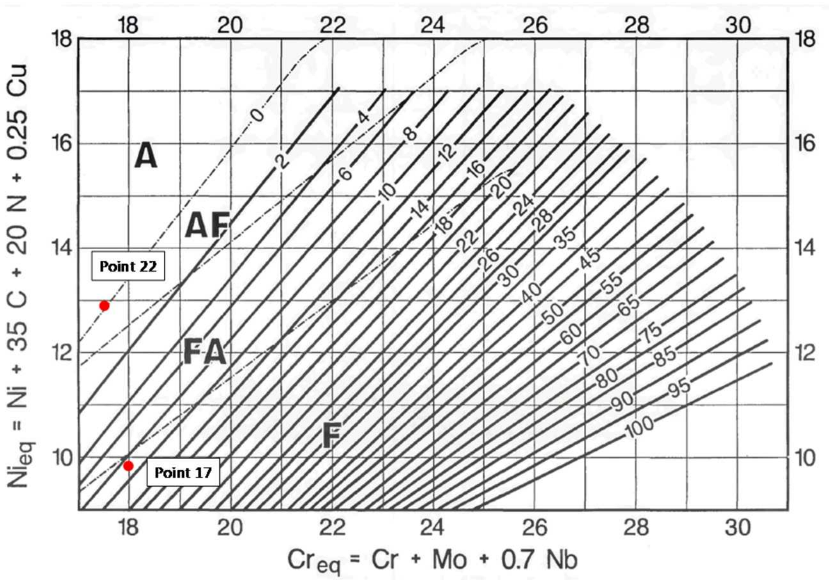
Note, EPMA scans did not include C and N; however, their presence would increase the Ni_{eq}, emphasizing the solidification mode shift



	Fe	Cr	Ni	Mn	Si	Cr_{eq}	Ni_{eq}	Cr_{eq}/Ni_{eq}
Point 1	70.77	18.72	8.54	1.63	0.35	18.72	8.54	2.19
Point 28	65.82	17.17	15.46	1.27	0.28	17.17	15.46	1.11

Electron Probe Microanalysis (EPMA) and WRC-1992 Diagram





	Fe	Cr	Ni	Mn	Si	Cr_{eq}	Ni_{eq}	Cr_{eq}/Ni_{eq}
Point 17	70.337	18.019	9.822	1.491	0.330	18.02	9.82	1.83
Point 22	67.934	17.551	12.877	1.354	0.284	17.55	12.88	1.36

*Mo, Nb, Cu may not be present.

*Scans did not include C and N; however, their presence would increase the Ni_{eq}, emphasizing the solidification mode shift

D.J. Kotecki, T.A. Siewart, Welding Journal, 71(5): 171s-178s, 1992.

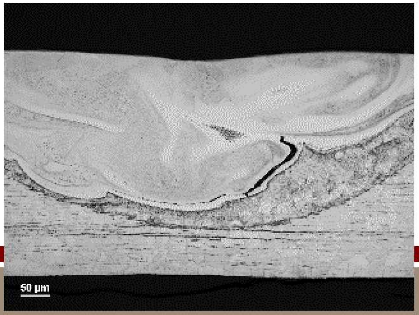
Type II Boundary Cracking

- Transition from unmixed zone with primary F mode solidification to mixed Ni-rich zone with primary A mode solidification results in a (interphase boundary during solidification, γ/γ grain boundary after cooling) boundary parallel to the fusion zone boundary (Type II boundary).

- This Type II grain boundary may migrate in the solid state further into the weld metal within a steep compositional and temperature gradient.

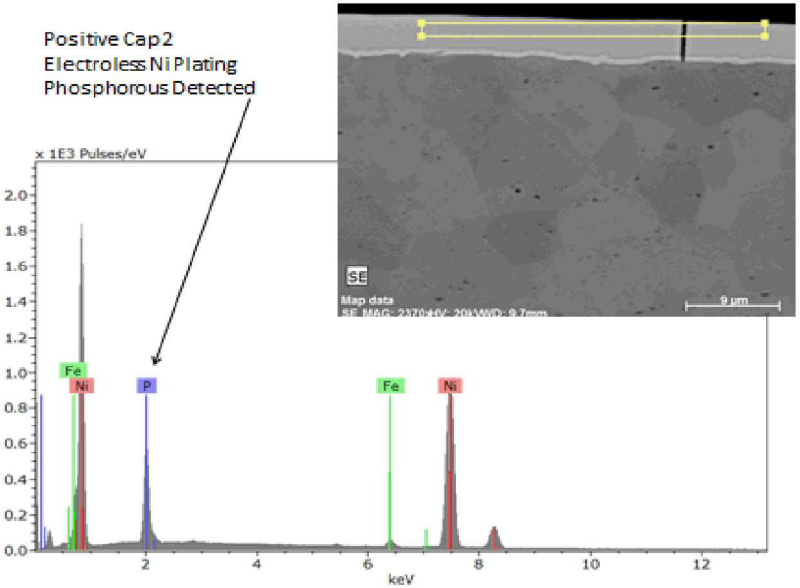
- In laser welded battery tabs, Type II cracking is more prominent in deeper welds with transition to keyhole mode; fusion boundary and Type II boundary oriented more perpendicular to the sheet. Cracks open up most prominently on the “vertically oriented” boundary region, similar to traditional hot cracks, although some shrinkage stress may exist in these shallow spot welds in the through-thickness direction as well.

T.W. Nelson, J.C. Lippold, and M.J. Mills, *Welding Journal*, 267s-277s, 2000.



Electroless Ni(P) plated terminals

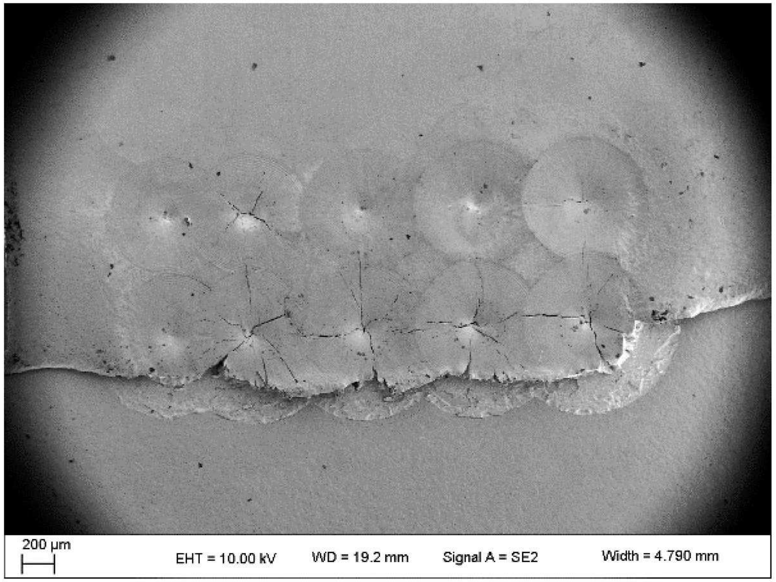
- Electroless Ni plating contains high amounts of phosphorous. Phosphorous is well known to be very detrimental in welding, high cracking tendency.
- Initial laser welding (and resistance welding) trials showed significant cracking; weld schedule too hot with excessive melting. Lower heat-input during welding reduces, but doesn't eliminate, cracking problems with Ni(P).

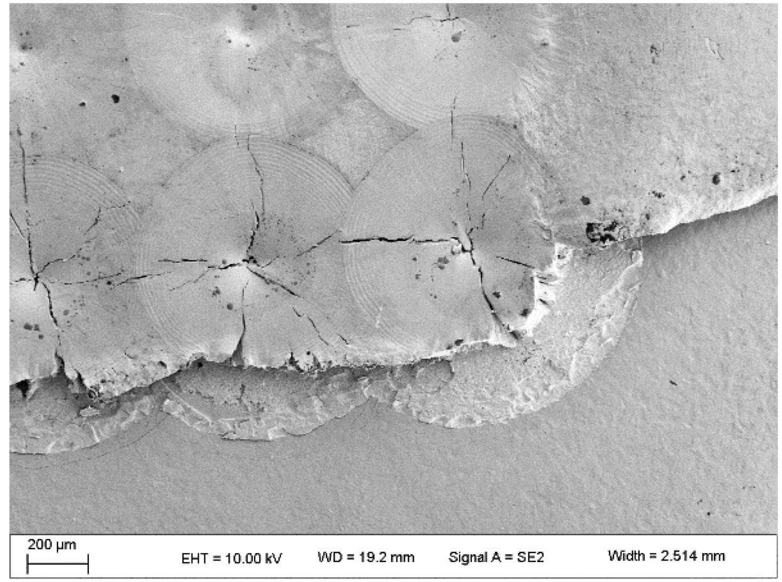


Weld schedule too hot

Lower heat-input weld schedule

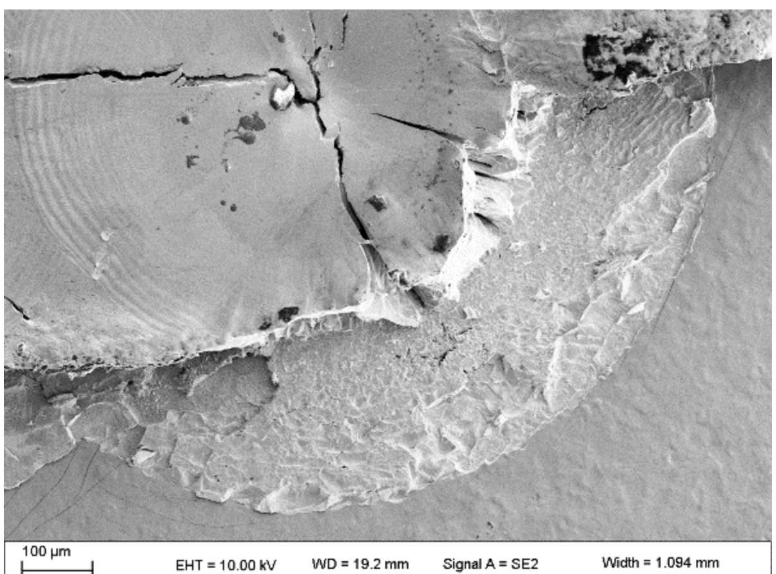
Cracks oriented radially from center of each spot; generally do not affect pull strength as much as "if cracks were oriented perpendicular to applied stress"

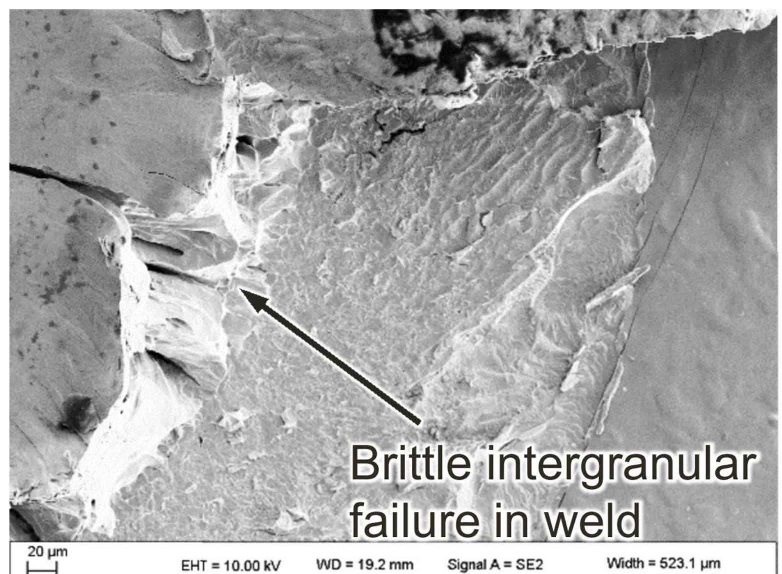




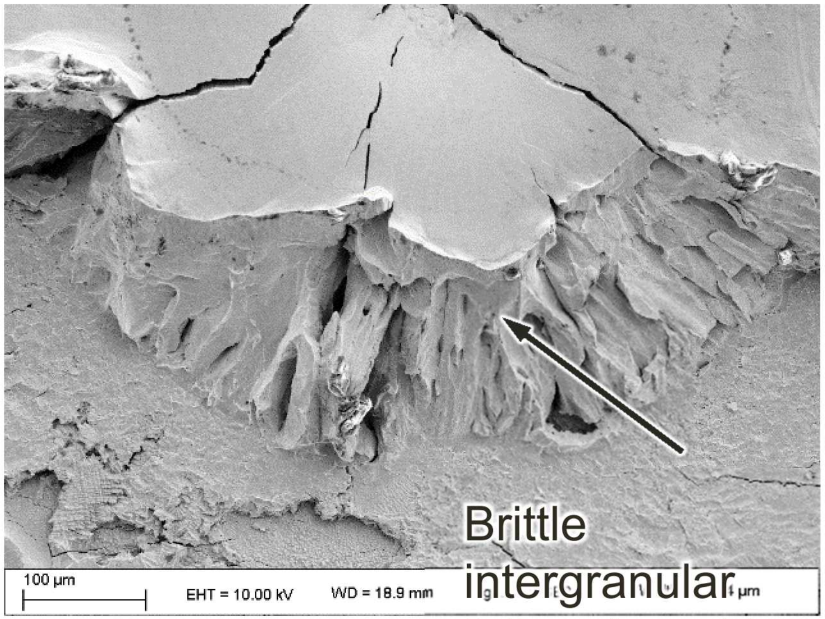
Pull-test failures still occur at periphery of the weld spots.

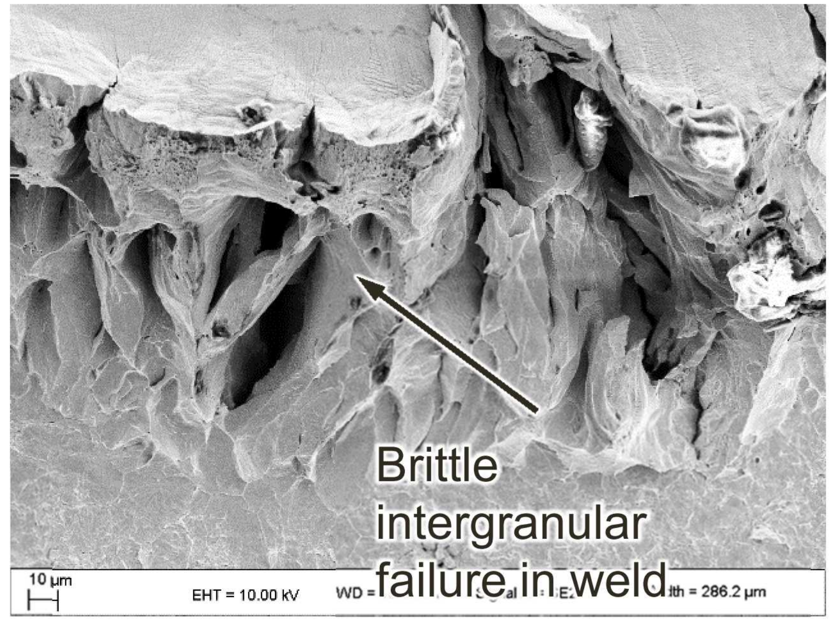
Weld cracks are likely sub-solidus cracking due to embrittlement





Of more concern is the brittle nature of the pull-test fracture due to embrittling effect of high P

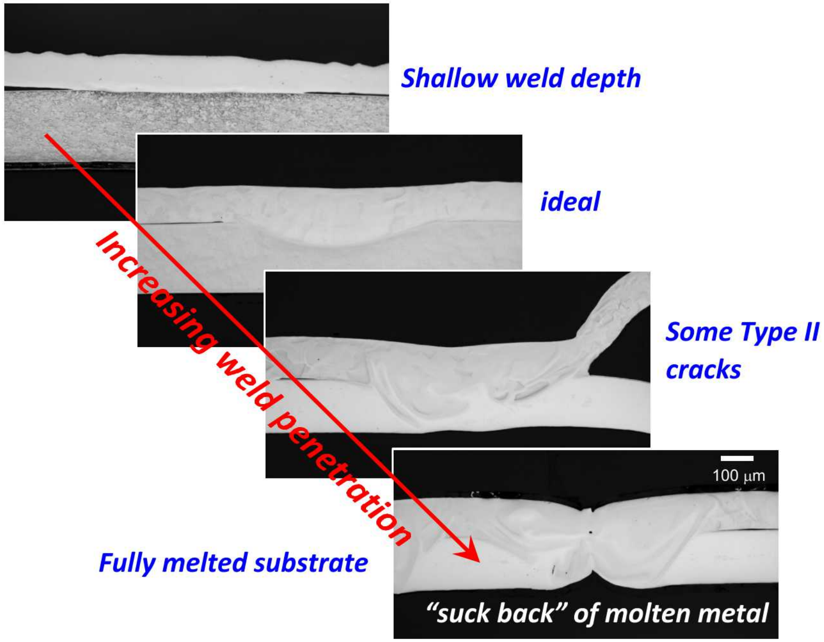




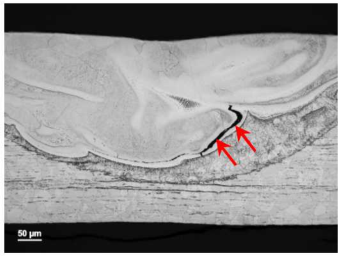
- Other than grinding or etching away the plating layer prior to welding, no viable solution identified yet to overcome the high-P issues
- For now, we can “live with” cracking because the pull strengths and variability are acceptable

Summary

- Laser spot welding is being developed to replace legacy resistance welding of battery tabs/terminals. *High strength is required but cannot breach the thin battery material.*
- Shallow, but wide conduction mode laser welds with high strength are possible. Welds with deeper penetration (keyhole mode), eventually result in substrate breach when the entire substrate becomes molten. Electroless Ni(P) plated substrates are problematic.



- Interesting solidification defect -- "Type II boundary cracking" -- were found in dissimilar welds between Ni sheet and 304L SS or carbon steel terminals. *Why not use 304L sheet & make similar welds??? The other end of the tab must be soldered and pure Ni is preferred.* More work needed to understand cracking.
- Even with some cracking present, pull strengths are high (often >40 lbs. force), with fracture in the Ni sheet in some cases.



Solidification defect in dissimilar Ni/304LSS laser spot weld

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