

# Metallography of Battery Resistance Spot Welds

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Li-ion cells provide an energy dense solution for systems that require rechargeable electrical power. However, these cells can undergo thermal runaway, the point at which the cell becomes thermally unstable and results in hot gas, flame, electrolyte leakage, and in some cases explosion. The heat and fire associated with this type of event is generally violent and can subsequently cause damage to the surrounding system or present a dangerous risk to the personnel nearby. The space flight environment is especially sensitive to risks particularly when it involves potential for fire within the habitable volume of the International Space Station (ISS).

In larger battery packs such as Robonaut 2 (R2), numerous Li-ion cells are placed in parallel-series configurations to obtain the required stack voltage and desired run-time or to meet specific power requirements. This raises a second and less obvious concern for batteries that undergo certification for space flight use: the joining quality at the resistance spot weld of battery cells to component wires/leads and battery tabs, bus bars or other electronic components and assemblies.

Resistance spot welds undergo materials evaluation, visual inspection, conductivity (resistivity) testing, destructive peel testing, and metallurgical examination in accordance with applicable NASA Process Specifications. Welded components are cross-sectioned to ensure they are free of cracks or voids open to any exterior surface. Pore and voids contained within the weld zone but not open to an exterior surface, and are not determined to have sharp notch like characteristics, shall be acceptable [1].

Depending on requirements, some battery cells are constructed of aluminum canisters while others are constructed of steel. Process specific weld schedules must be developed and certified for each possible joining combination. The aluminum canisters' positive terminals were particularly difficult to weld due to a bi-metal strip that comes ultrasonically pre-welded by the manufacturer. This was further complicated as the maximum electrode force was limited to low-electrode force to prevent deflection of the aluminum can during welding. Other Li-ion cells are comprised of smaller diameter cylindrical steel canisters which are inherently capable of handling greater force from the electrodes. Allowing higher-electrode forces aids greatly in insuring a consistent resistance network for the weld.

Various strategies were used to include adding projections to the tabs, slotting the tabs, and developing special electrode shapes. Essential variables such as load, time, power, voltage, and current also needed to be optimized to produce robust and defect-free welds.

Overall lessons learned:

- Developing good jigs is critical to insure the parts and electrodes are planer to one another and the location of the weld sites remains accurate and repeatable.
- Maintaining strict control over materials is critical. Materials must be of a specific hardness and chemical composition to insure that a weld schedule is repeatable.

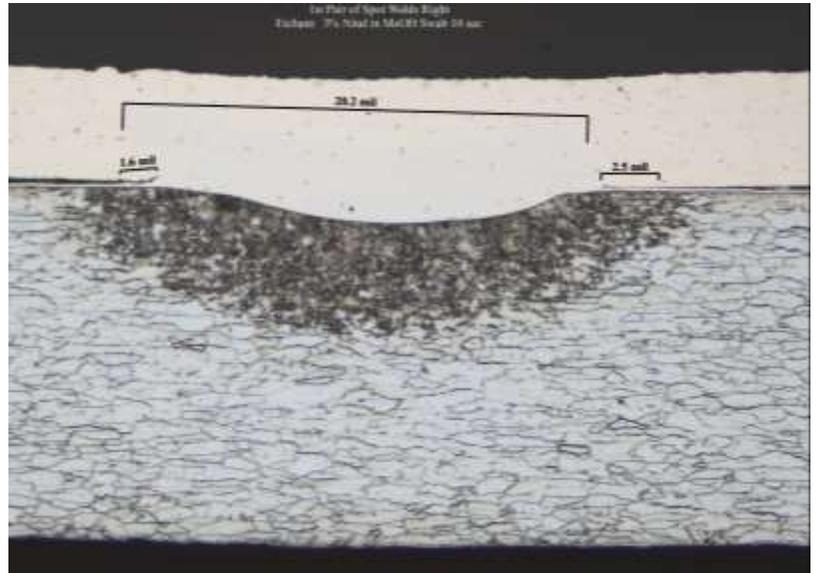
- Accuracy of the die used to stamp the projections is critical and worth the investment.
- Proper seasoning of the electrodes is critical to producing consistent welds. Once the electrodes have been properly seasoned, cleaning/dressing should be avoided until it is absolutely necessary.

Reference:

[1] NASA PRC-0009 Resistance Spot Welding of Battery Assemblies.



**Figure 1.** Robonaut 2 Aboard the ISS.



**Figure 2.** Nickel-Steel Spot Weld with Cracks on Both Sides of Interface.



**Figure 3.** Nickel-Steel Cathode Showing Overload Deflection

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## Metallography of Battery Resistance Spot Welds

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## Background

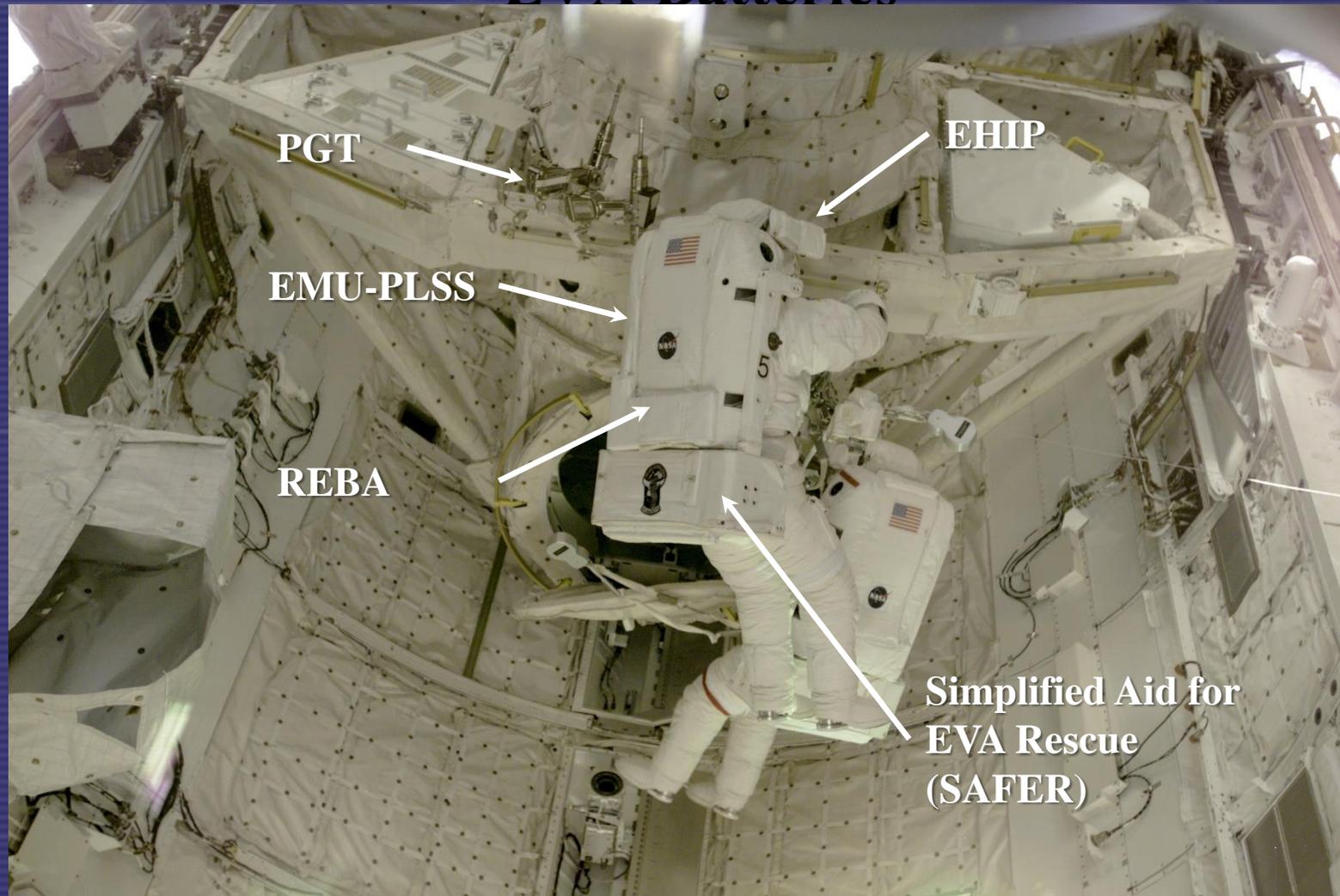
- Li-ion batteries are rechargeable (secondary) sources used as energy storage devices, generally connected to and charged by a prime energy source, delivering their energy to the load on demand.
  - Secondary batteries are used in applications that include power for satellites, astronaut suits, planetary and lunar rovers, and surface systems during night-time or peak power operations. Payloads, launch vehicles, and portable devices, such as computers and camcorders, may also use secondary batteries in place of primary batteries for cost savings, to handle power levels beyond the capability of conventional primary batteries, or because of activation, rate capability, or life issues.<sup>[1]</sup>
- Li-ion cells provide an energy dense solution for systems that require rechargeable electrical power. In larger battery packs such as Robonaut 2 (R2), several hundred Li-ion cells are placed in parallel-series configurations to obtain the required stack voltage and desired run-time or to meet specific power requirements.

<sup>[1]</sup> NASA Engineering and Safety Center (NESC) Technical Report, Guidelines on Lithium-ion Battery Use in Space Applications, NASA Aerospace Battery Life Program

## Where Do We Use Batteries?

- Extra Vehicular Activity (EVA) Applications:
  - Increased Capacity Li-ion Battery for Extra Mobility Unit-Primary Life Support System (EMU-PLSS)
  - Pistol Grip Tool (PGT)
  - Helmet Interchangeable Portable Light (EHIP)
  - Glove Heater and Helmet Camera [Rechargeable EVA Battery Assembly – (REBA)]
  - Simplified Aid For EVA Rescue (SAFER) <sup>[2]</sup>
- IVA Applications:
  - Power Drill, Camcorders, Laptops, WCCS, Crew Escape Suit
- Primary Structures:
  - ISS, Visiting Vehicles, Orion Crew Module
- Robotics:
  - Robonaut 2
  - Space Exploration Vehicle (SEV)

# EVA Batteries



PGT

EHIP

EMU-PLSS

REBA

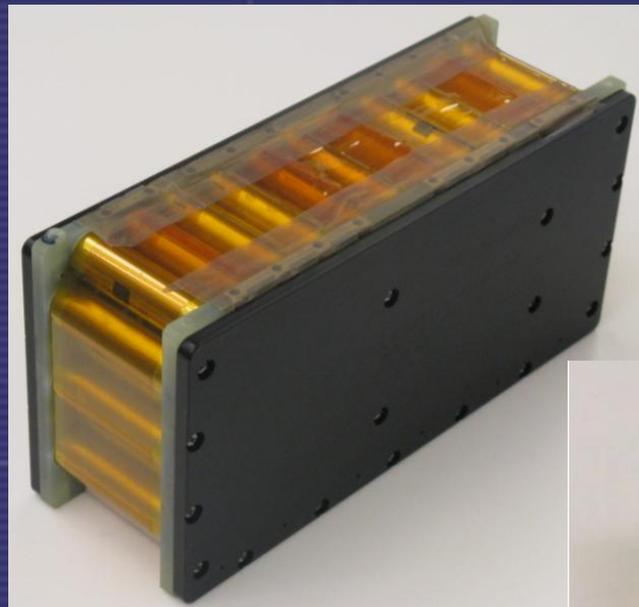
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EVA Rescue  
(SAFER)

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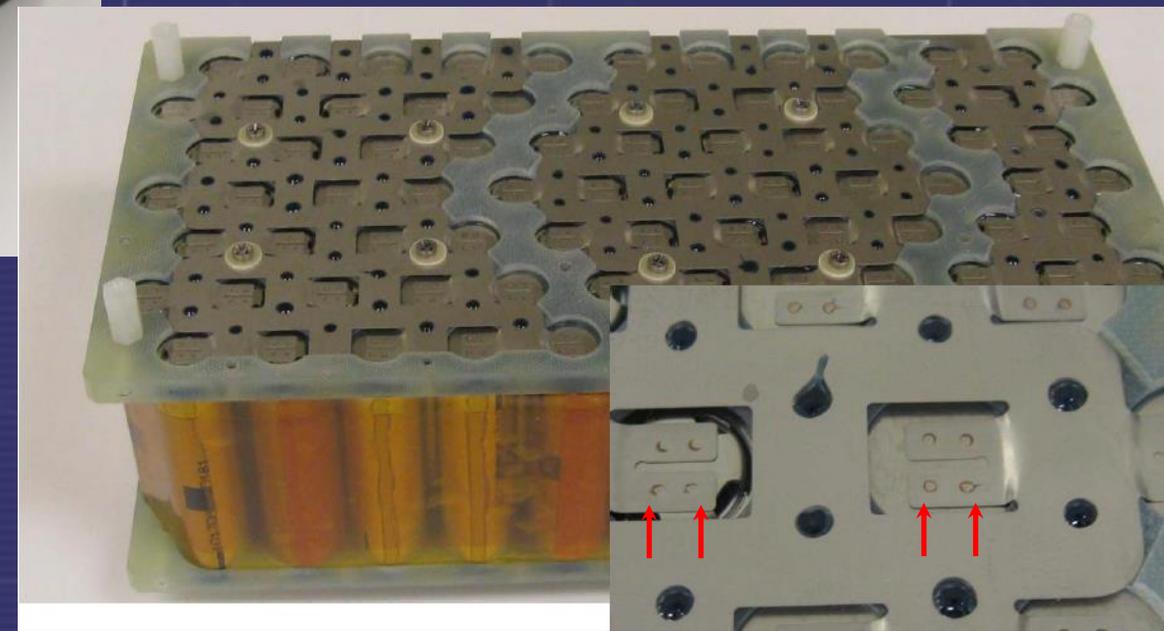
# EVA Batteries



EMU Battery



Close-up of Ni bus plate to cell spot welds



# Robotics Batteries



R2



SEV

## Welding Variables & Strategies

- Depending on requirements, some battery cells are constructed of aluminum canisters while others are constructed of steel canisters.
  - Process specific weld schedules must be developed and certified for each possible joining combination.
  - The aluminum canisters' positive terminals are particularly difficult to weld due to a bi-metal strip that is ultrasonically pre-welded by the manufacturer. This is further complicated as the maximum electrode force was limited to low-electrode force to prevent deflection of the aluminum can during welding.
  - Other Li-ion cells are comprised of smaller diameter cylindrical steel canisters, which are inherently capable of handling greater force from the electrodes. Allowing higher-electrode forces aids greatly in insuring a consistent resistance network for the weld.
- Various strategies are used to include adding projections to the tabs, slotting the tabs, and developing special electrode shapes. Essential variables such as load, time, power, voltage, and current also need to be optimized to produce robust and defect-free welds.

## Examples of RSW Batteries



16850 Li-Ion Battery  
(Steel Can, Nickel Tab)

Swing 5300 Li-Ion Battery  
(Aluminum Can, Nickel Tab)

When joining components for batteries that undergo certification for human spaceflight use, the joining quality at the resistance spot weld of battery cells to component wires/leads and battery tabs, bus bars or other electronic components and assemblies shall be evaluated.

# Governing Document:

## Process Specification for the Resistance Spot Welding of Battery and Electronic Assemblies (NASA PRC-0009)

### 1.0 SCOPE

This process specification provides the requirements that govern the Resistance Spot Welding (RSW) of battery tabs and component wires/leads to batteries, battery tabs, or other associated electronic components. Procedural and quality assurance requirements are given. All work instructions and Weld Procedure Specifications (WPSs) used during welding shall satisfy the requirements of this process specification and its applicable documents.

### 2.0 APPLICABILITY

This process specification applies to the RSW of battery assemblies and associated electronic flight and non flight hardware fabricated under the control of the NASA/Johnson Space Center (JSC). RSW with opposed electrodes (i.e., referred to herein as “opposed welding”) is considered as well as RSW with gapped electrodes (i.e., referred to herein as “series welding”). Battery assemblies are considered to be non structural with no load carrying capacity and shall be either potted, taped, shrink wrapped, or installed in a rigid containment to preclude stressing the tabs and lead wires.

- Resistance spot welds undergo materials evaluation, visual inspection, conductivity (resistivity) testing, destructive peel testing, and metallurgical examination in accordance with applicable NASA Process Specifications (PRC-00009 Resistance Spot Welding of Battery Assemblies).
- Welded components are cross-sectioned to ensure they are free of cracks or voids open to any exterior surface. Pore and voids contained within the weld zone but not open to an exterior surface, and are not determined to have sharp notch like characteristics, shall be acceptable. <sup>[3]</sup>

## Standard Definition of RSW

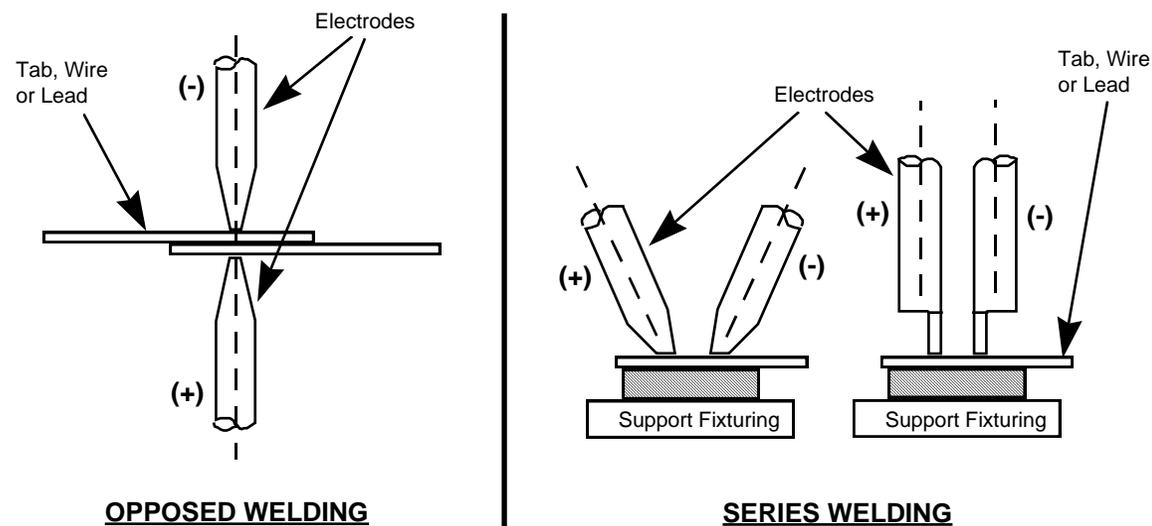


Figure 2 - Opposed and Series Welding

Opposed Welding – Resistance Spot Welding (RSW) utilizes two electrodes positioned exactly opposite and in line with each other (electrodes share a common axis). Each electrode contacts a single piece of base material. Each weld cycle produces only one fused spot.

Series Welding – RSW utilizes two electrodes positioned adjacent to each other but separated by an air gap or other dielectric. Each electrode contacts the same surface of base material. This type of welding is utilized where access to both sides of the weld joint is physically restricted or if a component damage would result if the welding current were to shunt through the system circuit or electrical component. Support tooling opposing the force of the electrodes is insulated from the welding circuit and therefore does not shunt current from the welding circuit and therefore does not shut current from the welding circuit. Each weld cycle produces two fused spots. The electrodes can be positioned parallel or at a fixed angle to each other. <sup>[4]</sup>

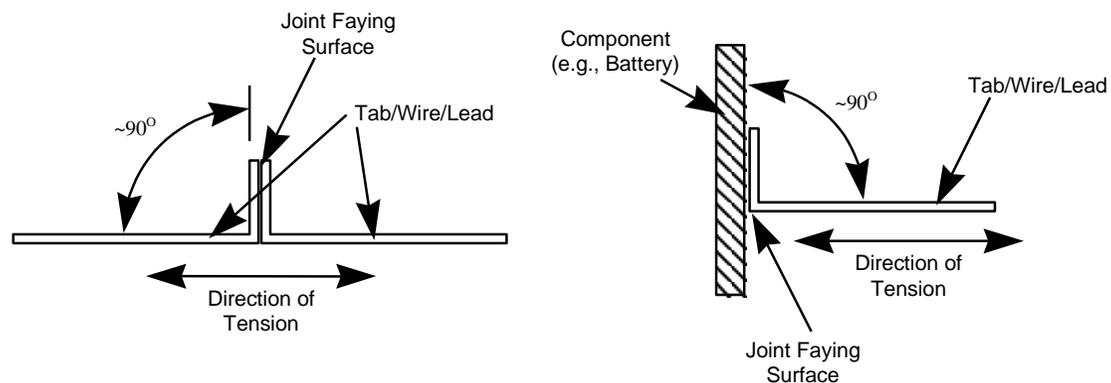
<sup>[4]</sup> American Welding Society (AWS) Standards

ANSI/AWS A2.4 – *Standard Symbols for Welding, Brazing and Nondestructive Testing*

ANSI/AWS A3.0 – *Standard Welding Terms and Definitions*

## Destructive Peel Testing

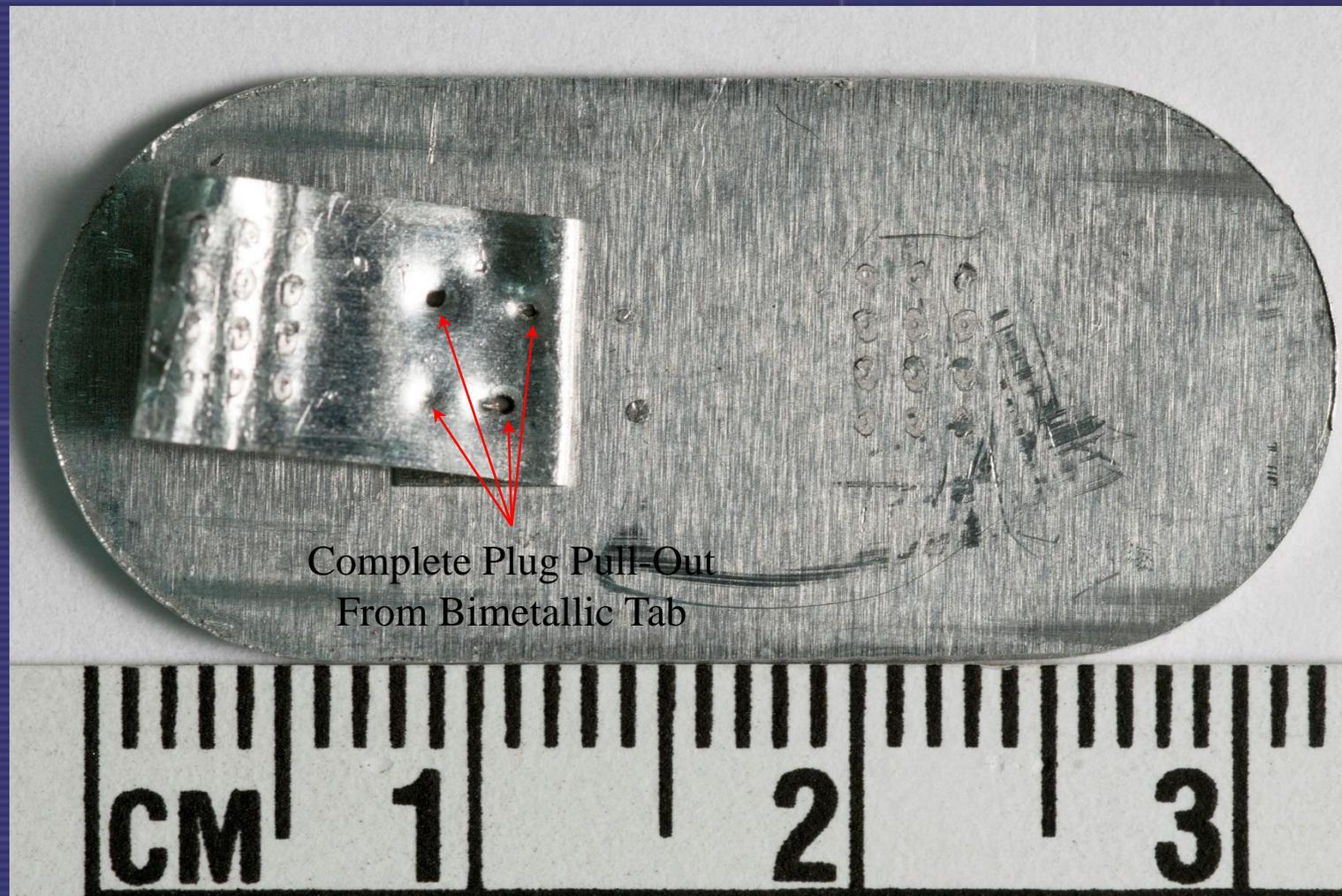
### 6.2.4.4 DESTRUCTIVE PEEL TESTING



**Figure 3 - Peel Test Examples**

Fifteen (15) weld samples shall be peel tested. The edges of a spot welded sample connection shall be gripped and pulled apart to failure. The welded connection (lap joint) shall be pulled in tension at an approximate  $90^\circ$  angle to the plane of the faying joint surfaces. See Figure 3. The length of the grip sections on the samples shall be long enough to preclude any interference of the gripping hardware with the welded connection. For a procedure qualification or preproduction verification sample set to be considered acceptable, the result of the peel test must be a plug pull-out in a minimum of 75% of the total number of individual spots in the sample set for connections with 4 or more spots, 85% for connections with 3 spots only, and 100% for connections with 2 or less spots. If any of the individual samples from the 15 peel tests fail to result in at least 2 plug pull-outs from the total number of weld spots on the individual connection, 2 additional welded sample connections may be welded and submitted for inspection and testing as part of the initial sample set, one time only. These 2 samples shall then be factored into the above acceptance criteria. If more than 2 samples from the original lot fail the peel test as described above, further weld parameter development or process analysis to determine the cause for the failure(s) is required prior to submitting another 16 samples for testing to the requirements of this specification. If the minimum plug pull-out requirement for the total number of individual spots in the sample set (i.e., 75%, 85%, or 100% for the respective condition) can not be met as described above, further weld parameter development or process analysis to determine the cause for the failure is required prior to submitting another lot of samples for testing to the requirements of this specification.

# Peel Test of Nickel Tab on Battery Bimetallic Tab

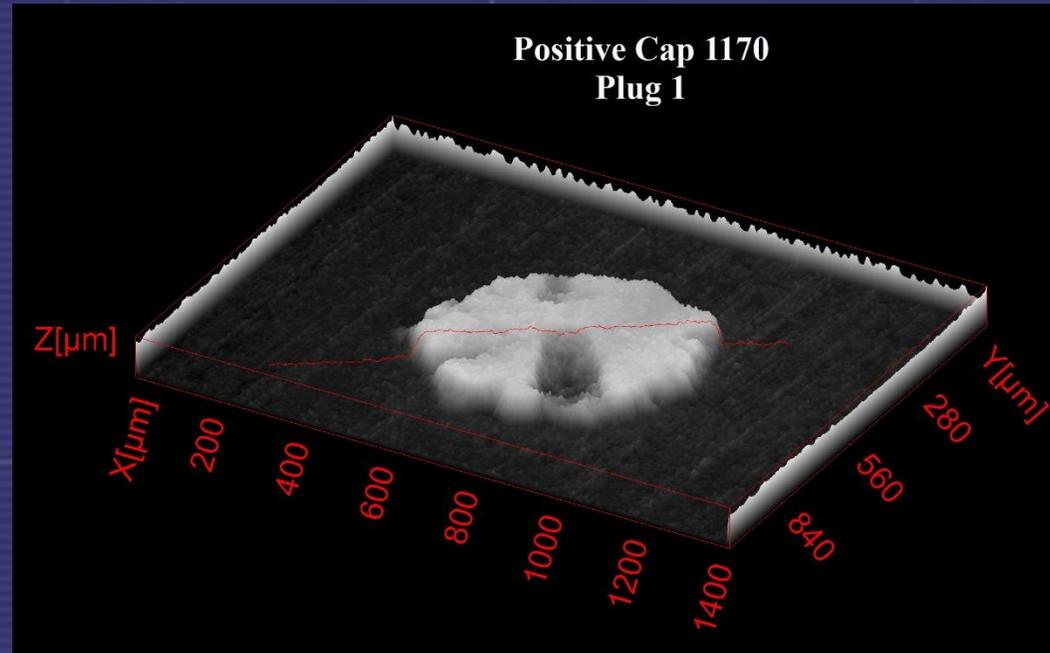


Complete Plug Pull-Out  
From Bimetallic Tab

# Topographic Image of Plug 1 from Positive Cap 1710



Plug 1 Pull-Out  
From Bimetallic Tab

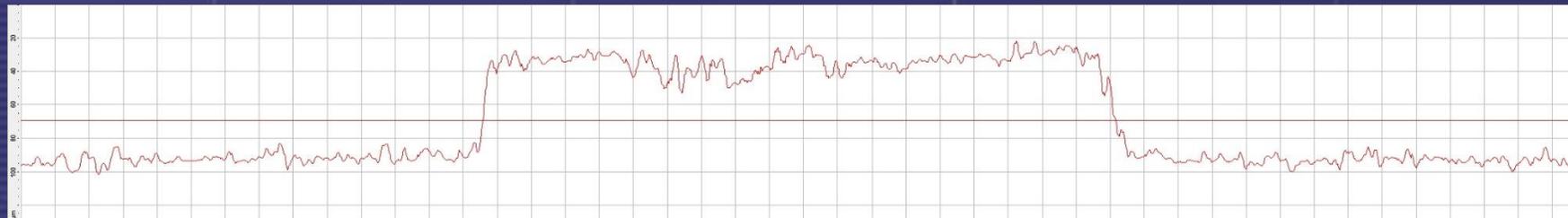
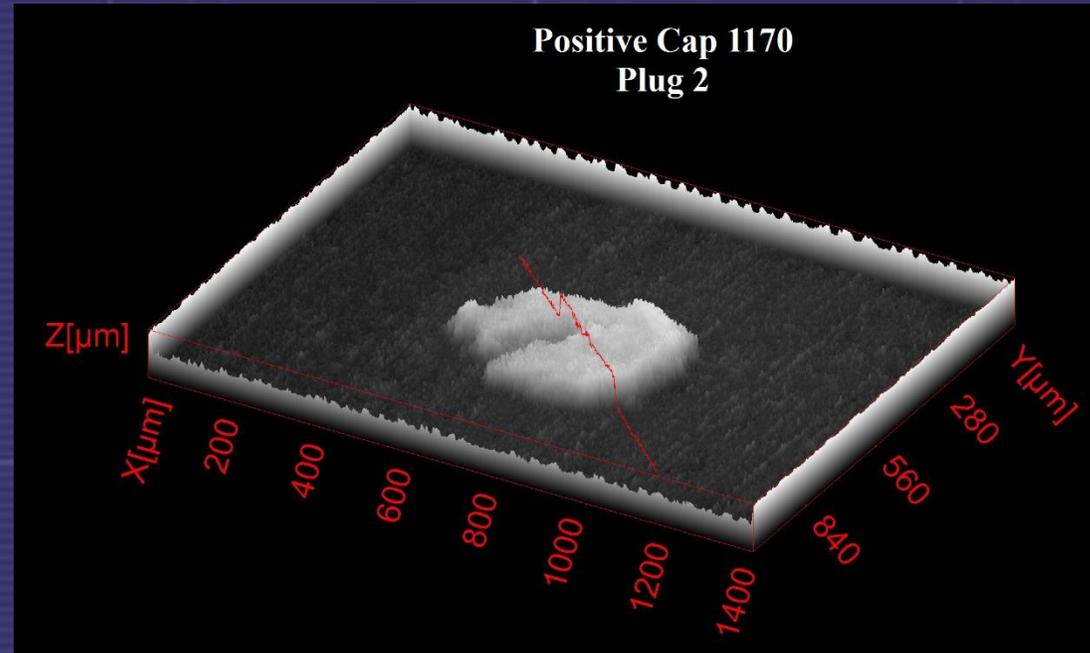


Max height: +69  $\mu\text{m}$  (~2.7 mils)

# Topographic Image of Plug 2 from Positive Cap



Plug 2 Pull-Out  
From Bimetallic Tab



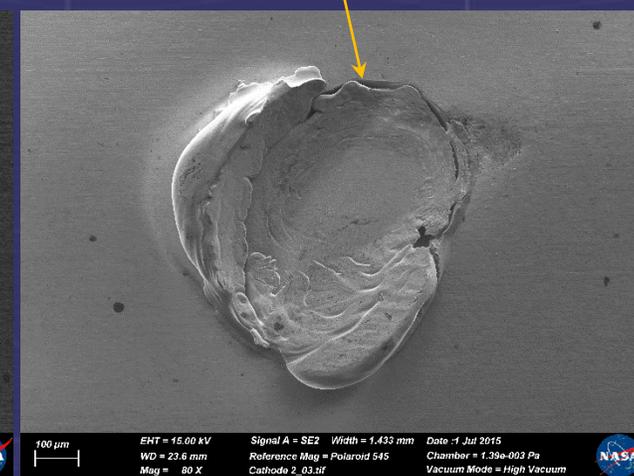
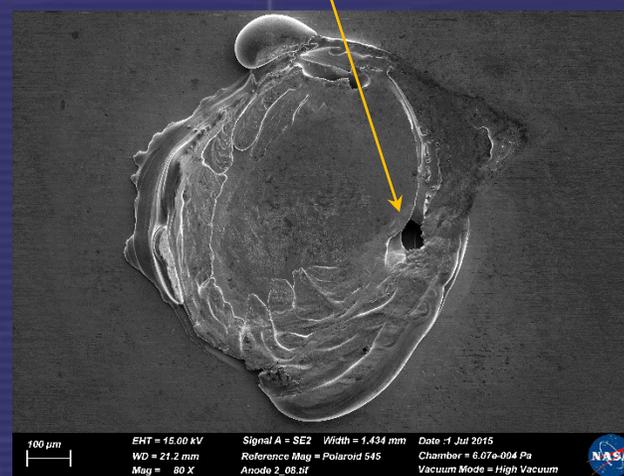
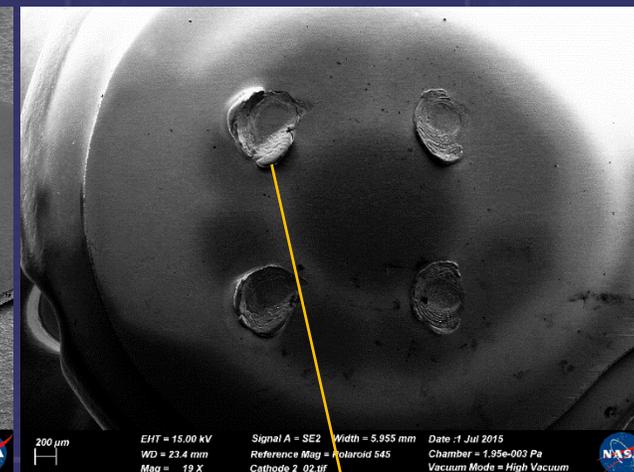
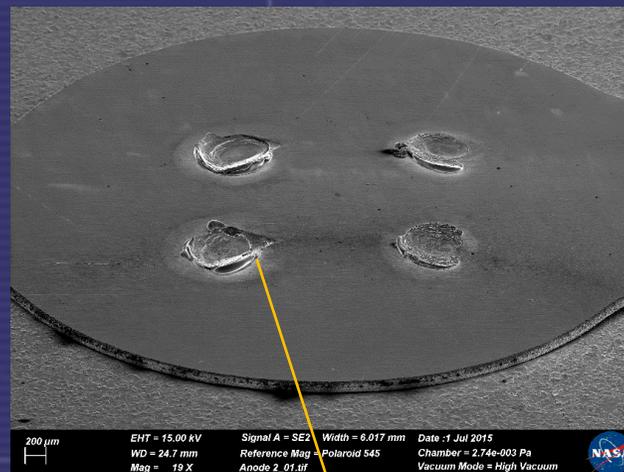
Max height: +60  $\mu\text{m}$  (~2.4 mil)

## Visual Inspection of RSW

### 7.3 VISUAL INSPECTION

All welds shall be inspected visually at a magnification of 30X. The welds shall conform to the following visual inspection criteria:

- Cracked Weld** - Any weld that exhibits a crack in the weld zone shall be rejected.
- Pitted/Deformed Weld** - Any weld that exhibits pits, holes or voids open to the surface, in either of the materials being shall be rejected. Surface deformation or upset from electrode contact shall not be considered unless the area in question exhibits sharp notch like characteristics, severe oxidation due to overheating, or where either of the elements has been deformed/upset by more than 50% of the material thickness.
- Metal Expulsion** - Any weld that exhibits metal expulsion where the molten metal has become separated from the weld area shall be rejected.
- Electrode Deposit** - Significant deposits of the electrode tip being left on the weld surface shall be rejected. Topical shallow deposits and superficial marks shall not be considered.
- Open Weld** - An open weld shall be rejected. An open weld is one in which a weld has been attempted but no bonding has occurred.
- Missed Weld** - Any weld that has been specified on the drawings but has been overlooked by the welding operator shall be identified and welded to meet the drawing requirements.

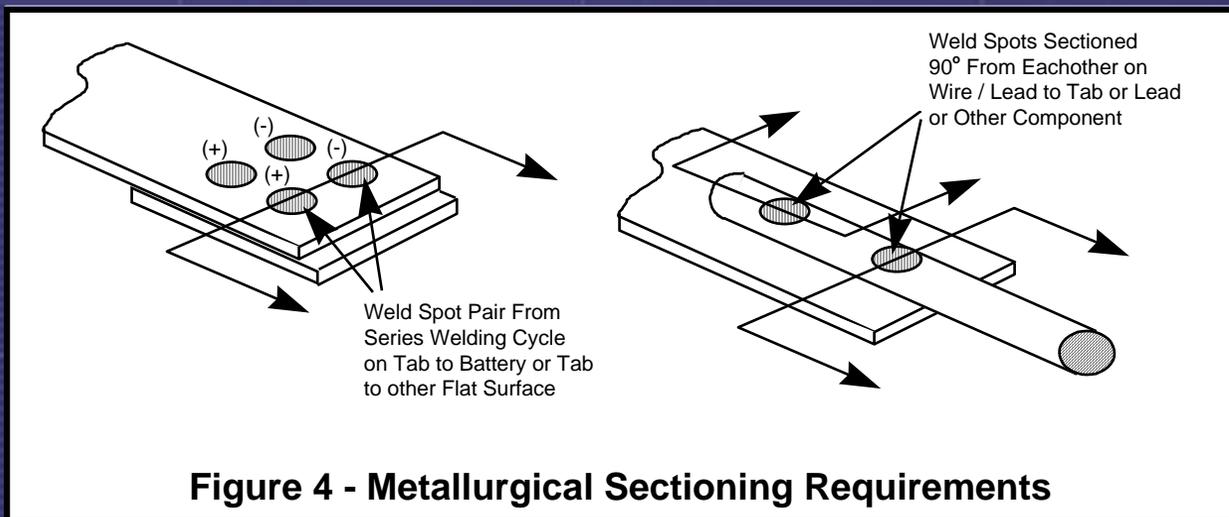


# Metallurgical Sectioning

## 6.2.4.5 Metallurgical Examination

When required, one (1) of the 16 samples submitted shall be cross-sectioned, mounted, polished, and etched for metallurgical examination. For samples involving a wire or component leads, one each weld spot on the connection will be cross sectioned transverse to the wire diameter and longitudinal to the wire diameter axis and for Series Welded samples, cross sections of both weld spots produced by one weld cycle (welds produced under each electrode contact ) shall be taken. See Figure 4.

The welds shall be free of cracks or voids open to any exterior surface. Pore and voids contained within the weld zone but not open to an exterior surface, and are not determined to have sharp notch like characteristics, shall be acceptable. When examining welds intended for battery cells, any anomaly which is determined to be a potential for breaching or degrading the battery housing and therefore potentially causing a leak, shall be cause for rejection. In addition, a metallurgical fusion bond shall be visible at each weld spot interface. If this criteria cannot be met, further weld parameter development or process analysis to determine the cause for the rejectable condition, is required prior to submitting another lot of samples for testing to the requirements of this specification.



**Figure 4 - Metallurgical Sectioning Requirements**

## Metallography of Battery Caps



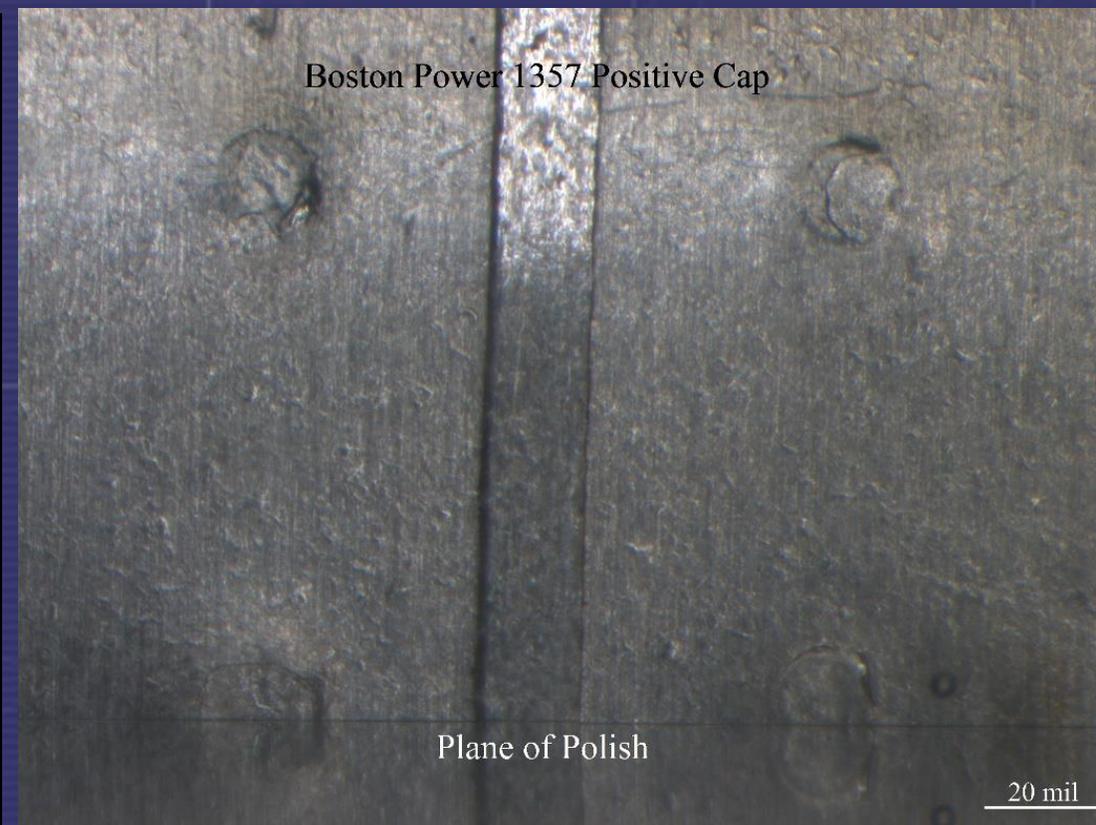
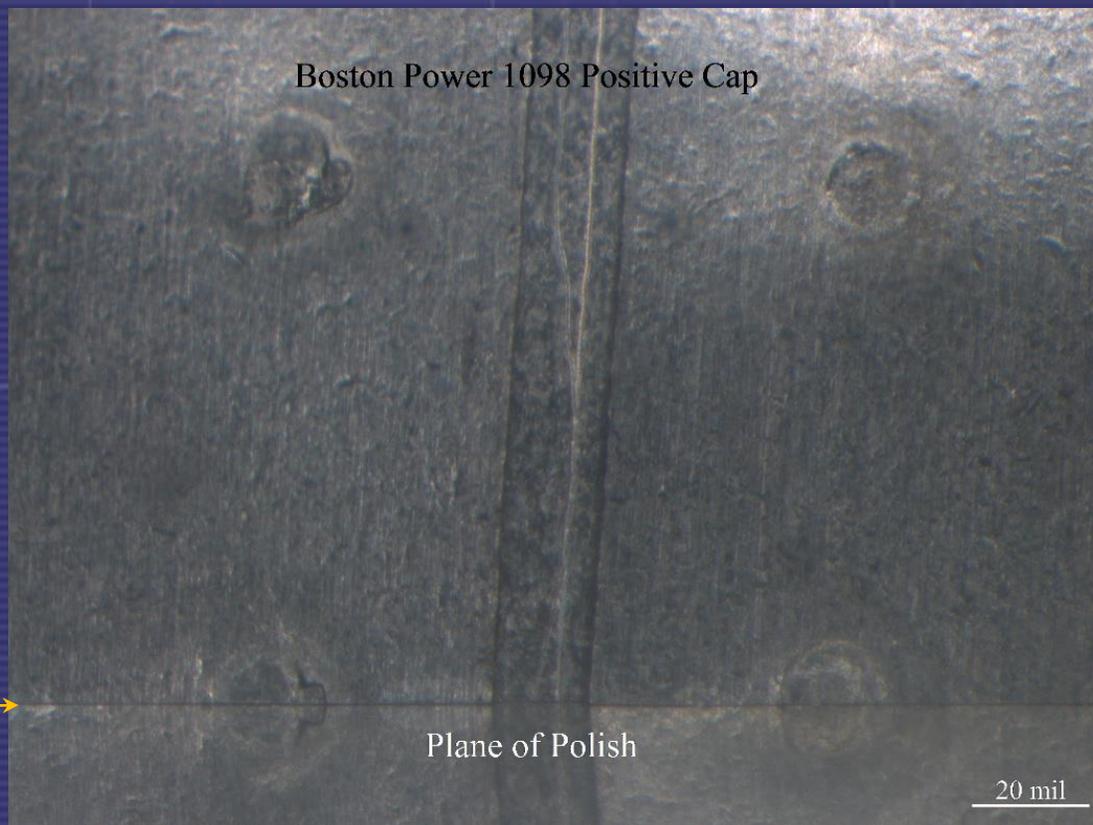
16850 Li-Ion Battery Cathode  
(Steel Can, Nickel Tab)



16850 Li-Ion Battery Anode  
(Steel Can, Nickel Tab)

- Battery caps are removed from cylinder. Caps are then cold-mounted in 2-part epoxy.
- A side window is polished near the spot welds to view the cross-section polishing plane position. This step is necessary to ensure the cross-section plane-of-polish is at the center of RSW.

## Stereo Image of Spot Welds Through Epoxy Viewed from the Side Window of Cold Mount

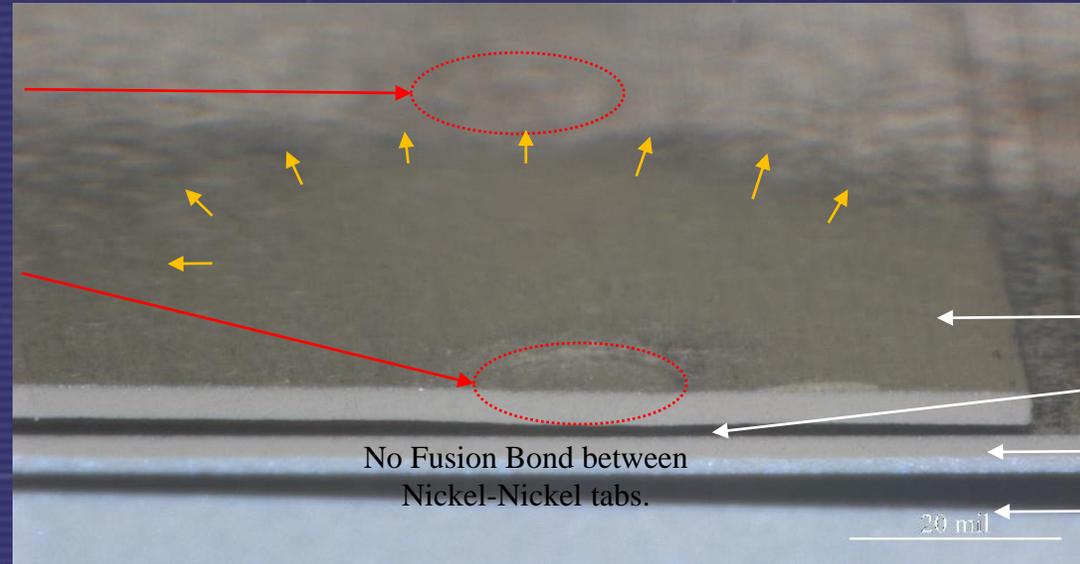


Plane of Polish is at Center of Both Sets of 1<sup>st</sup> Pair Resistance of RSW.  
Subsequent polishing performed on 2<sup>nd</sup> Pair.

### 35x Stereo Image of Boston Power Positive Cap (1<sup>st</sup> Pair) Taken at 45°

2<sup>nd</sup> Spot Weld  
(undisturbed weld further  
inside the epoxy)

1<sup>st</sup> Spot Weld  
(captured through center)



Gold arrows show the crease line where the nickel tab was bent upwards, forming in a gap between the Ni and bimetallic tabs resulting in an open weld.

Nickel Tab

Gap between Ni and Bimetallic Tab (open weld)

Bi-metallic Tab

Battery Cap

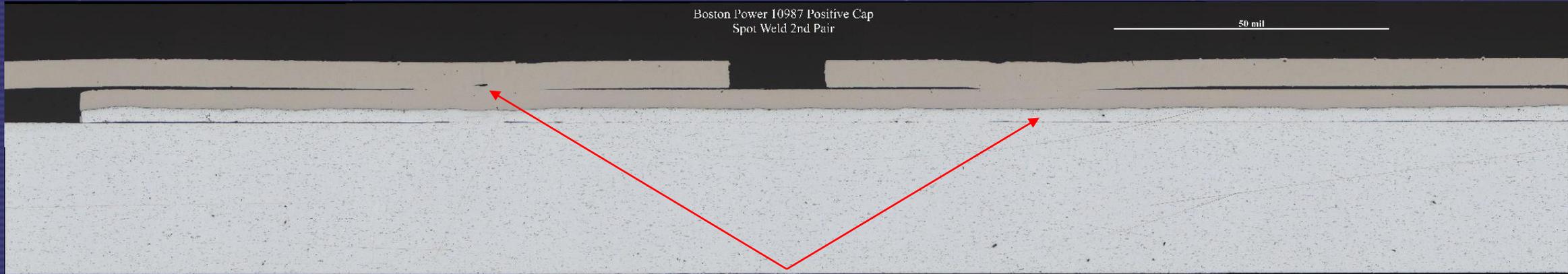
No Fusion Bond between Nickel-Nickel tabs.



Open Weld. No Fusion Bond between Nickel-Nickel tabs.

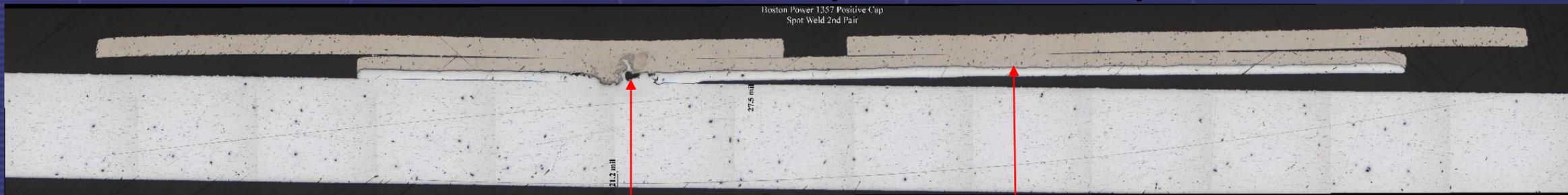
This spot weld looks good.

### RSW of Bi-Metallic Strip to Aluminum Cap



Both Nickel-Nickel spot welds look good. One small void on left weld. Note how bimetallic tab is contacting cap on both weld locations.

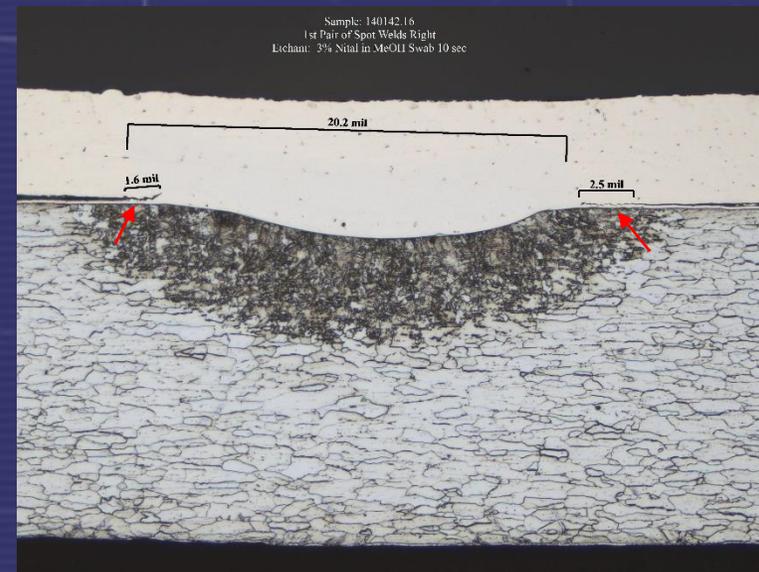
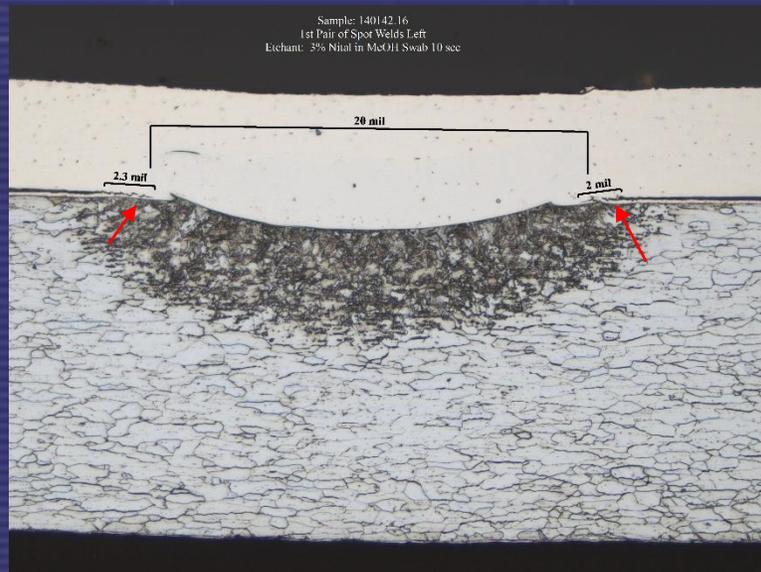
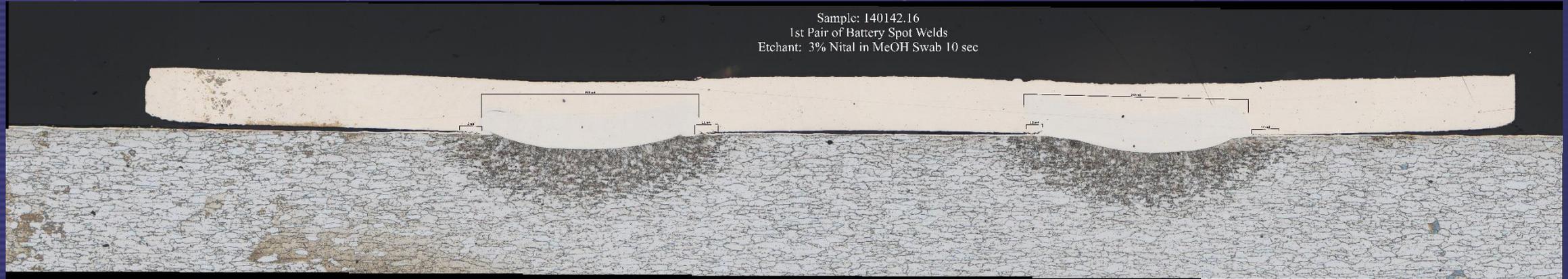
### RSW of Bi-Metallic Strip to Aluminum Cap



Cracks and Voids Present

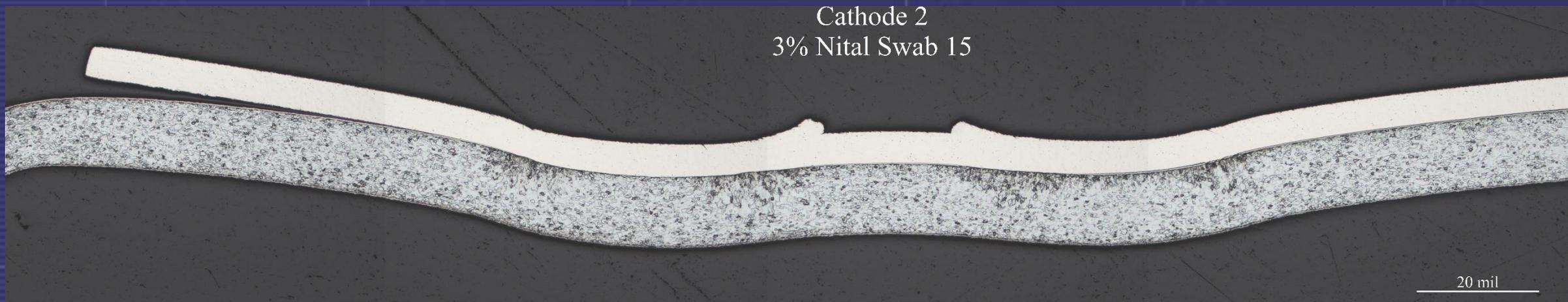
This spot weld looks good. Note the tilt between bimetallic tab and cap.

## RSW of Nickel-Steel Battery Cap Showing Cracks at Both Interfaces



Cracks at Interfaces (red arrows)

## RSW of Nickel-Steel Battery Cap Showing Overload Deflection



Excess load was applied to battery cap resulting in overload deflection

## Lessons Learned

- Developing good jigs is critical to insure the parts and electrodes are planar to one another and the location of the weld sites remains accurate and repeatable.
- Maintaining strict control over materials is critical. Materials must be of a specific hardness and chemical composition to insure that a weld schedule is repeatable.
- Accuracy of the die used to stamp the projections is critical and worth the investment.
- Proper seasoning of the electrodes is critical to producing consistent welds. Once the electrodes have been properly seasoned, cleaning/dressing should be avoided until it is absolutely necessary.

## References

[1] NASA Engineering and Safety Center (NESC) Technical Report, NASA Aerospace Battery Life Program

<http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20090023862.pdf>

[2] Battery Applications for NASA's Missions - A Historical Perspective

[http://www.arpa-e.energy.gov/sites/default/files/documents/files/Miller\\_RANGE\\_Kickoff\\_2014.pdf](http://www.arpa-e.energy.gov/sites/default/files/documents/files/Miller_RANGE_Kickoff_2014.pdf)

[3] NASA PRC-0009 Resistance Spot Welding of Battery Assemblies

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