The Effect of Laser Surface Preparation on the Quality of Ultrasonic Wire Bonding Process in Battery Pack Assembly

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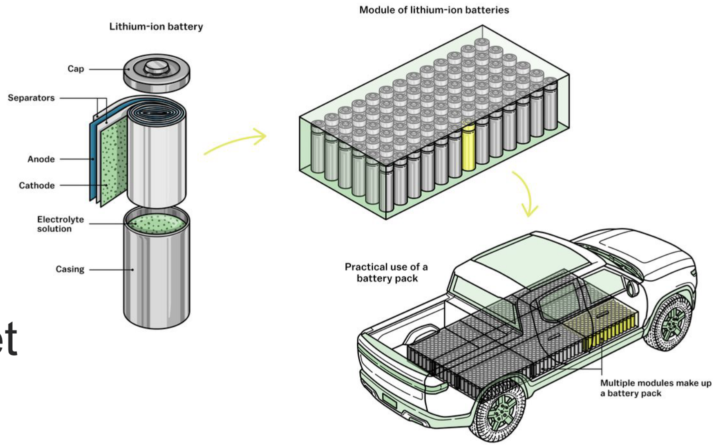
Introduction

- The global electric vehicle battery market size [1]
  - 2021: $23.8 billion
  - 2022-2031: CAGR of 16.6% – $108.2 billion
- A study published in U.S. International Trade Commission
  - Lithium-ion batteries → More than 70% of the rechargeable battery market
- Ultrasonic wire bonding (UWB) is the interconnection technology of choice for electric vehicle (EV) battery packs [4]
- The advantages of UWB for welding battery packs include:
  - Ability to provide high-strength joint with low resistance in short period of time to most busbar material and aluminum and steel cell casings.
  - No melting and microstructural change due to the solid-state nature of UWB.
- EWI is aware from several industry contacts that a typical challenge in battery manufacturing, especially for high-reliability wire bonding, is control of surface cleanliness and roughness for wire bonding.



An electric car with thousands of lithium-ion battery cells [2]

Wire Bonding process of Battery Pack [3]

Objective

EWI has discussed the cleanliness need for battery modules with Laser Marking Technologies (LMT).

LMT has developed and built a laser cleaning system for EWI to support this study.

Objective

Using laser cleaning technology to evaluate the effect of surface contamination and roughness on the quality of the bond in UWB process of aluminum wires to nickel-plated steel cells

Research Approach

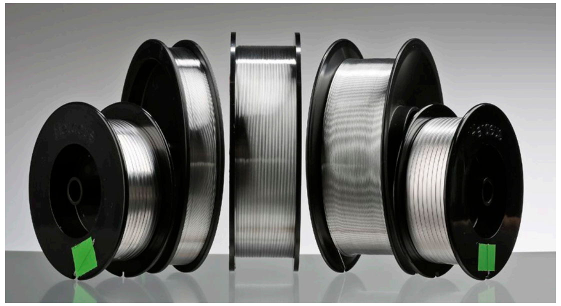
- This research has carried out in seven steps described below:

  - Step 1: Preparation of experimental setup
  - Step 2: Developing wire bonding parameters using screening trials
  - Step 3: Organization of the design of experiment (DOE)
  - Step 4: Running the experimental trials based on developed DOE in Step 3
  - Step 5: Measurement of the responses
  - Step 6: Data analysis

Experimental Setup

Laser Marking Technologies, LLC.

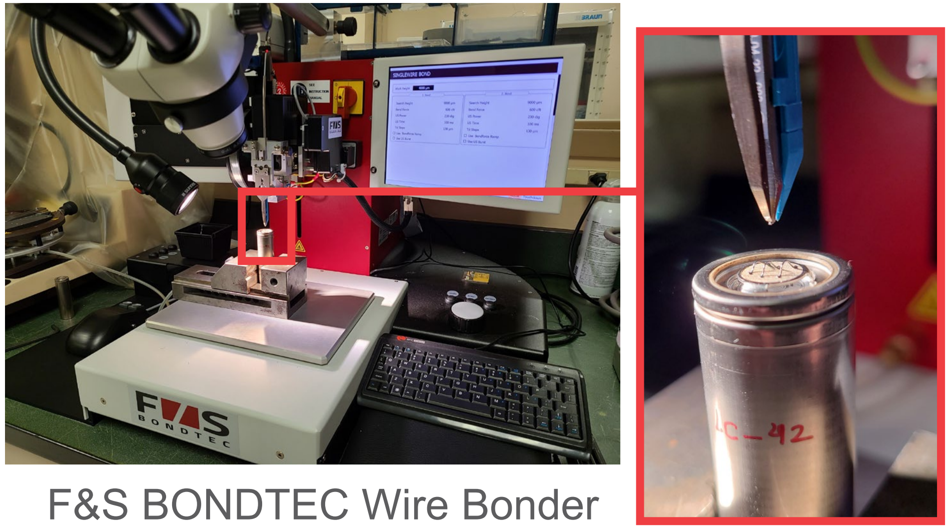
Cobalt-xl-ev-100PF laser making system
100-watt HO Ytterbium pulsed fiber LMT MOPA



Wire: Pure Aluminum
(Al-H11)

Recommended Technical Data of Al-H11					
Diameter	Microns (µm)	125	150	200	250
	Mils	5	6	8	10
Elongation	%	> 1	> 1	> 1	> 1
Breaking Load	cN	50 – 90	70 – 125	130 – 220	200 – 300

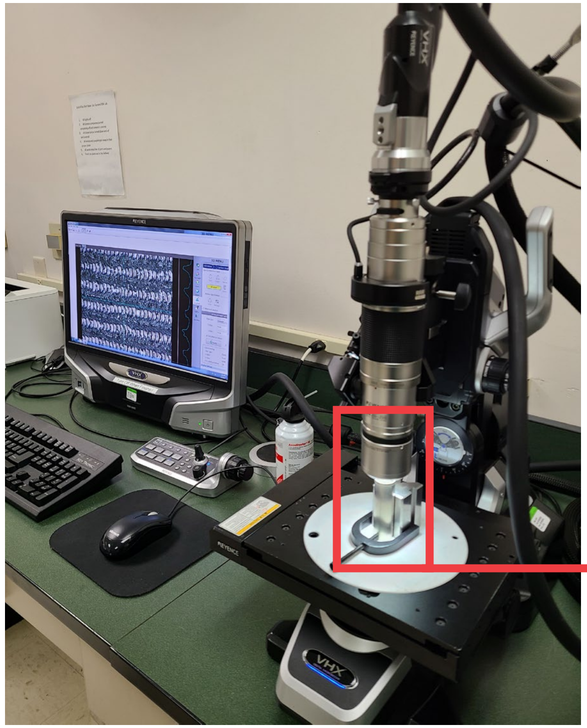
21700 Battery Cell

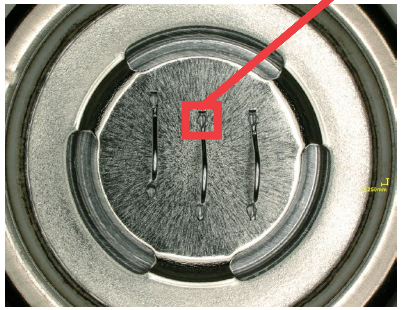


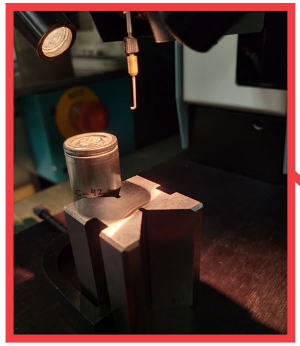
F&S BONDTEC Wire Bonder

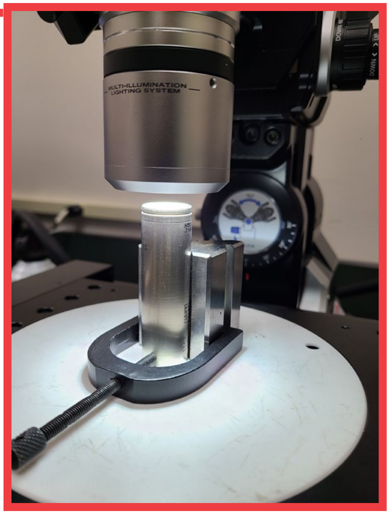
Blasocut 2000
Universal
Cutting fluid based
on Mineral Oil

Testing Equipment









Keyence microscope with high magnifying Lens

Evaluation of bonded wires and measurement of surface roughness

JASCO 4700 Fourier-transform Infrared Spectroscopy (FTIR)

Evaluation of surface contamination

Unitek wire bond pull tester

Wire bond strength

Screening Trials

- Screening trials were done on 21700 Cell to study the effects of wire bonding parameters (i.e., power and force) on bond strength using different time with and without contamination.

- Pull tests and microscopic images were used to evaluate the bonded wire and the settings that provided good bond were selected.
  - Underweld
  - Good weld
  - Overweld

Time = 200 ms					
Power (dig)	230	Underweld	Good weld	Good weld	Overweld
	200	Underweld	Underweld	Good weld	Overweld
	170	Underweld	Underweld	Underweld	Underweld
	140				
		2	6	10	14
		Force (N)			

Organization of DOE

- In this step, organization of the experiment, design selection, and assigning initial levels were addressed.
- The DOE was designed to provide sufficient resolution to address curvature and desired two-factor interactions.
- A specialty multilevel design in 24 trials was created.
- In this design, time, sample cleanliness, and surface roughness were included as input factors.

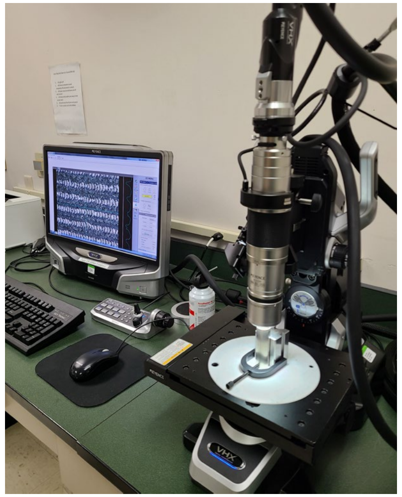
- DOE factors and their levels:
  - Wire bonding parameters:
    - Force and power: Constant → Based on screening trials
    - Time: four levels
      - 100 ms, 200 ms, 300 ms, 400 ms
  - Sample cleanliness: Two levels
    - No oil and with oil
  - Surface condition: Five levels
    - Surface as-is: Level 0 = ~ 1μm
    - Laser cleaned surface: four levels of roughness
      - Level 1 = 1.2 μm
      - Level 2 = 1.8 μm
      - Level 3 = 3.4 μm
      - Level 4 = 4.2 μm

Note: A separate DOE study was conducted to study the effect of laser cleaning parameters on the surface roughness.

Test Procedure

The test procedure used in this study was as follows:

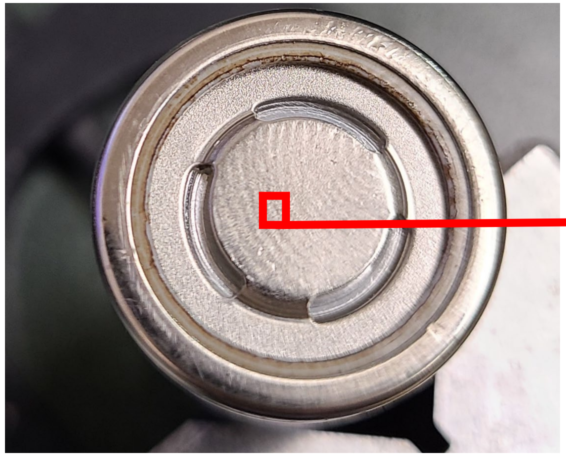
1. Cleaning all samples with isopropyl
2. Measurement of surface cleanliness and roughness
3. Half of the samples contaminated with an oily fingerprint
4. Measurement of surface cleanliness and roughness
5. Laser cleaning was done based on DOE plan.
6. Measurement of surface cleanliness and roughness
7. Ultrasonic wire bonding
8. Measurement of wire bond strength through pull testing



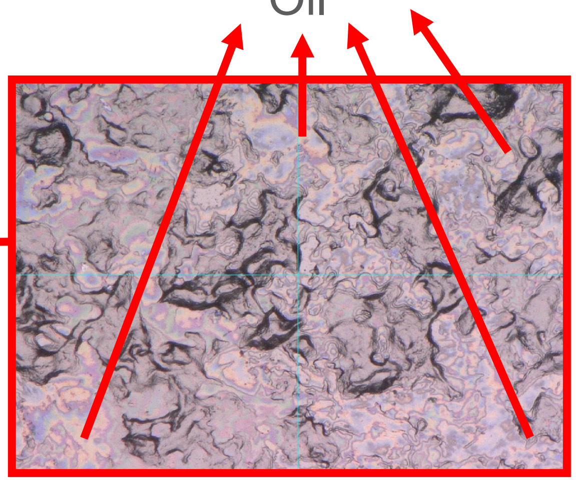
Measurement of the Responses - Surface Cleanliness

- JASCO 4700 Fourier-transform Infrared Spectroscopy (FTIR) with a diamond ATR attachment was used to scan the surface of the battery cells.
- Oil spectrum was identified by matching it to paraffinic mineral oil spectrum in Wiley's KnowItAll database.

JASCO 4700 FTIR



Contaminated Cell with an Oily Fingerprint

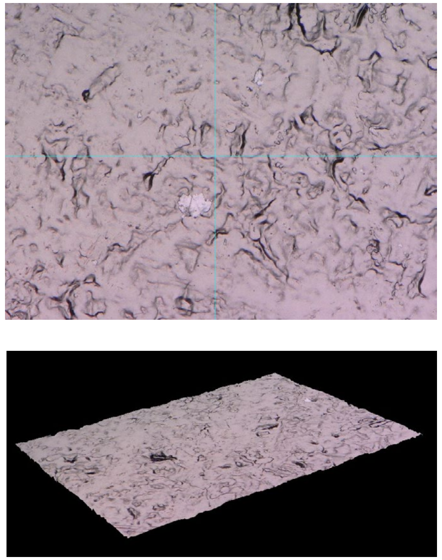


Microscopic Image of the Oily Surface (1000x magnification)

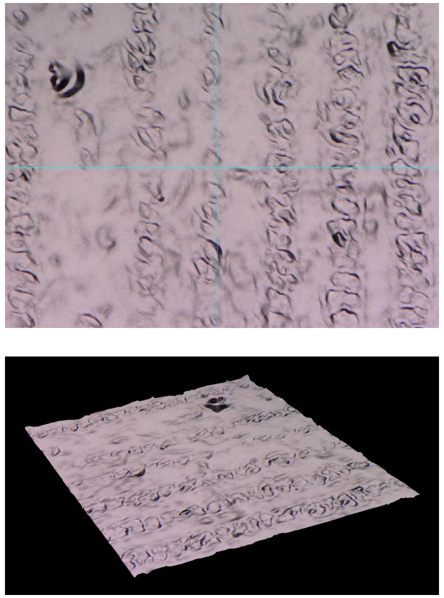
Laser Cleaning of 21700 Cell – Material: Nickel-plated Steel (Video)

Results – Surface Roughness Measurement

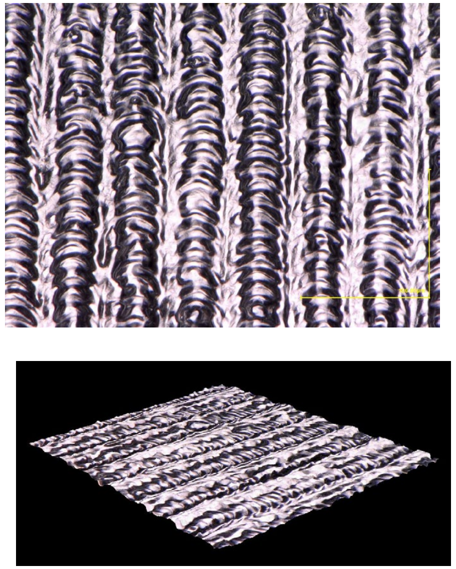
Level 1 Level 2 Level 3 Level 4



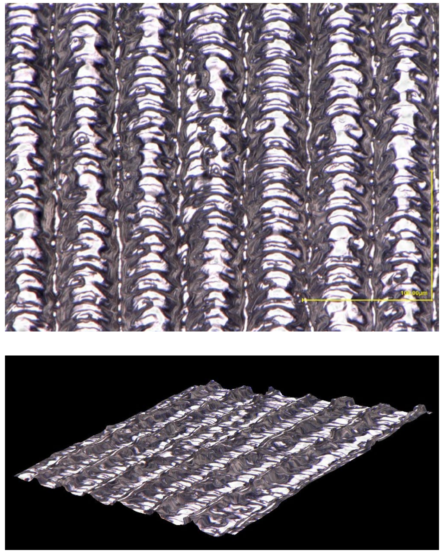
LC-53 (Level 0)
Ra= 0.95 µm
(No laser cleaning)



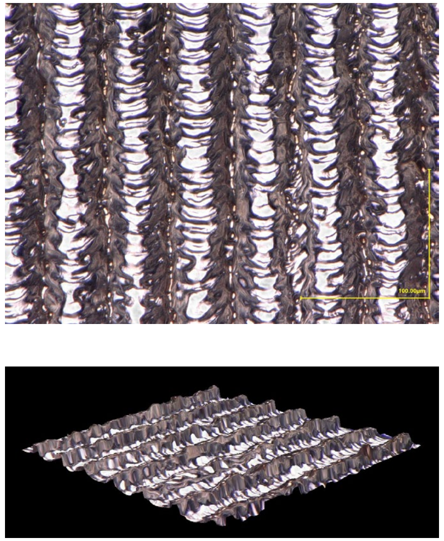
LC-53 (Level 1)
Ra= 1.2 µm



LC-44 (Level 2)
Ra= 1.8 µm



LC-46 (Level 3)
Ra= 3.4 µm

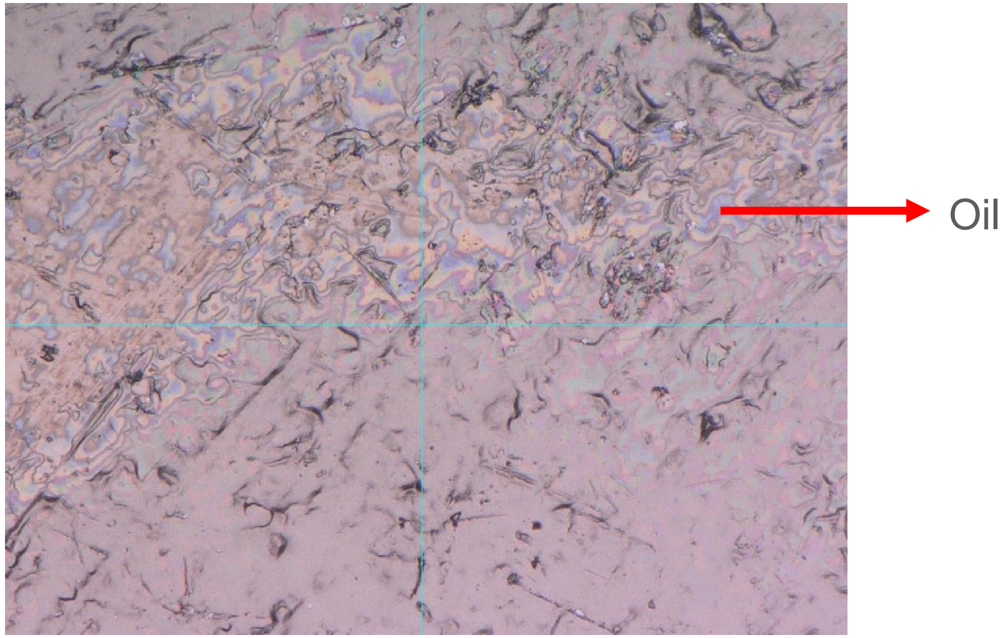


LC-56 (Level 4)
Ra= 4.2 µm

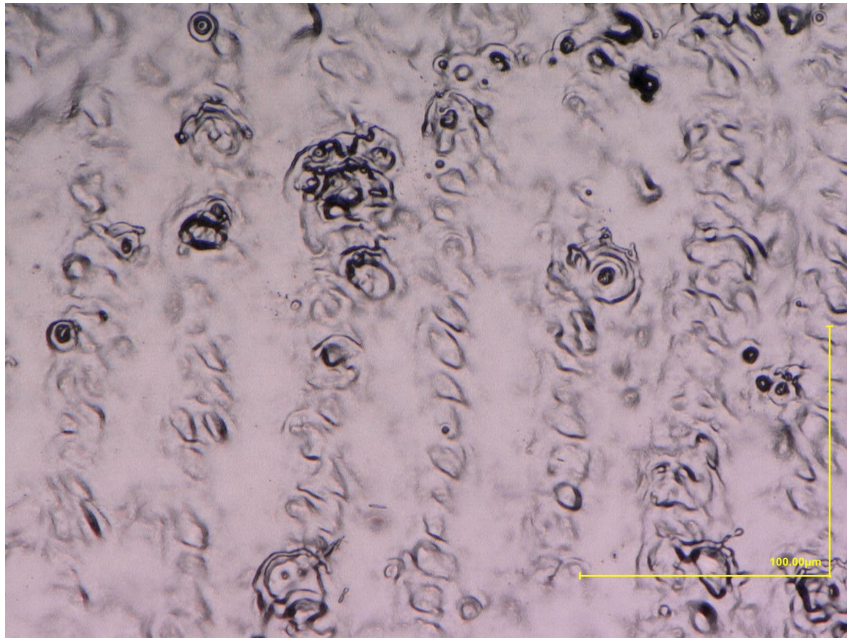
FTIR Results – Surface Cleanliness

- The spectrum of the cell before contamination showed no evidence of oil.
- Paraffinic mineral oil spectrum was identified by FTIR after testing the contaminated sample.
- The spectrum of the cleaned cell with laser was very similar to spectrum of the sample before contamination.

Laser cleaning was able to eliminate the oil from the surface of the cell.



Battery Cell after Contamination (LC-57)



Battery Cell after Laser Cleaning (LC-57)

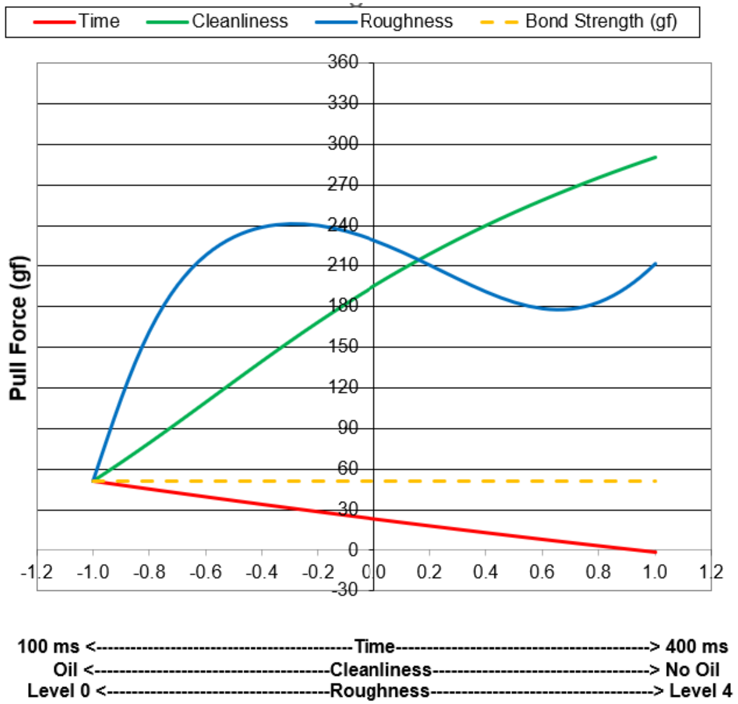
Statistical Analysis of the Results

- Statistical analyses were done using standard EWI techniques, which include data normalization, regression curve fitting, and process robustness plot preparation.
  - Data normalization achieved through processing pull test datasets through specific mathematical function which can effectively map the pull-force data onto a normal space.
  - Regression analyses were then used to quantify correlations between the input variables and the pull-force data, yielding a statistically significant set of inputs and correlating coefficients to each response variable.
  - Resulting regression equation used to build process robustness plots. These plots:
    - Allow optimizing processing conditions
    - Provide understanding of how individual input factors affect bond strength when varied from these optimized values.

Process Robustness Plot – Pull Force

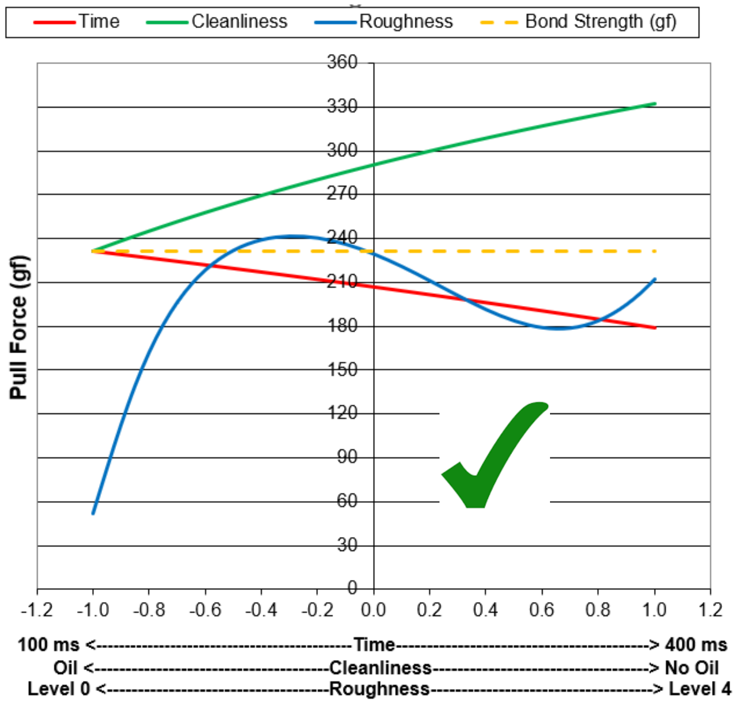
- Case study – Battery cells contaminated with oil

No laser cleaning - Level 0



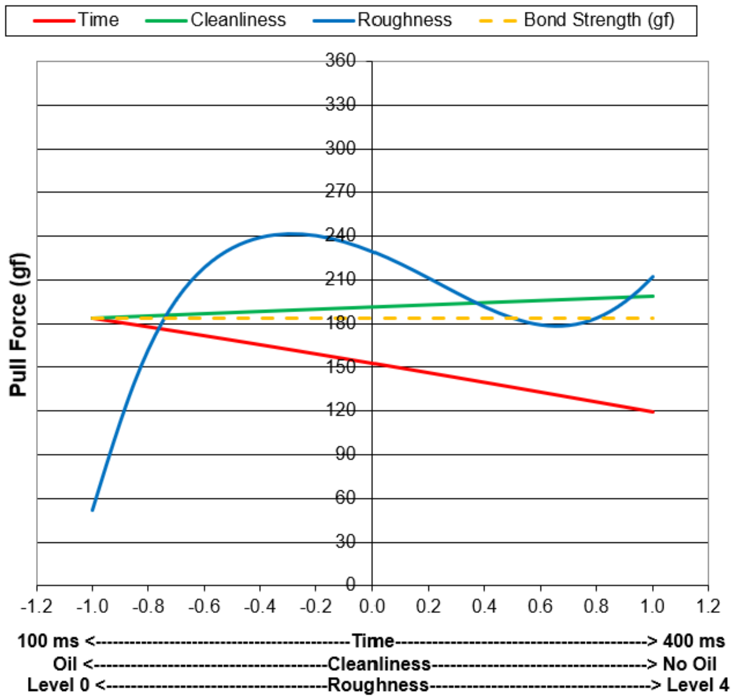
Bond strength (gf)	Time	Cleanliness	Roughness
51.5	100	Oil	Level 0

Laser cleaning – Level 1



Optimized Parameters			
Bond strength (gf)	Time	Cleanliness	Roughness
231.7	100	Oil	Level 1

Laser cleaning – Level 3



Bond strength (gf)	Time	Cleanliness	Roughness
183.5	100	Oil	Level 3

Summary and Conclusion

- In this study, laser cleaning technology was used to evaluate the effect of surface roughness and surface contamination on the quality of the bond in UWB process of aluminum wires to nickel-plated steel cells.
- The result of this study showed that:
  - <u>All levels of laser cleaning</u> can successfully <u>improve UWB process of the contaminated battery cells</u> by elimination of the oil from the surface of the battery cells which led to improve wire bond strength.
  - The <u>highest bond strength</u> was obtained when <u>low-intensity laser cleaning</u> (i.e., Level 1) was used while the <u>strength of the bonded wires decreased</u> at <u>higher intensity laser cleaning</u> (i.e., Levels 2-4), which could be due to creation of added oxidation at higher levels of laser cleaning.
- Extrapolation of these results to joining processes such as ultrasonic metal welding could be logical outcomes of this study.

References

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[4] Moghaddas, A. (2021). Ultrasonic Metal Welding for Lithium-Ion Battery Cells. https://ewi.org/ultrasonic-metal-welding-for-lithium-ion-battery-cells-2

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