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Improving Durability Of Wire Bonds In EV Batteries

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Wire bonding was developed and has long been used in semiconductor packaging because of its inherent flexibility and ease of programmability. These are the biggest advantages it has over other interconnecting methods. With wire bonding, electrical interconnections or wire bonds are created between the silicon die and its substrate using wires made of gold, aluminum, copper, silver alloys or palladium-coated copper composites.

Wire bonds are delicate with limited flexibility, and in semiconductors, they are usually encapsulated by buffer materials such as resin or mold compounds. These materials give them a measure of durability and strength to resist damage from vibration. But that measure of durability is lost in open-air applications in the majority of EV battery packs where there is no material to protect the wire bonds from the effects of vibration, leaving the wire bonds vulnerable to breakage.

In this article, we look at ultrasonic wire bonding as it is used for the interconnection of cylindrical lithium-ion (Li-ion) cells in EV battery packs. Specifically, we present a series of vibration tests that were conducted on wire bonds used in EV battery packs to determine the degree to which different aspects of wire bond design affect their susceptibility to breakage.

After discussing wire bond construction in EV battery packs and identifying the points of mechanical weakness, we introduce the test equipment that was developed to test wire bond vulnerabilities to vibration in this study. We then present the five comparison studies which we conducted to test the impact of vibration direction, material, wire shape, loop height, and single bond versus multiple wires.

The goal of these studies was to analyze the wire breakage problem in EV battery packs and to offer some mitigation solutions to reduce or eliminate the failure. After presenting the test results, we summarize the key findings that should help pack designers achieve greater ruggedness for wirebonds in EV battery packs.

Wire Bond Vulnerabilities In EV Battery Packs

Ultrasonic wire bonding is currently used for the interconnection of cylindrical Li-ion cells in EV battery packs. The negative wire is bonded to the cell rim while the positive wire is bonded to the cell center cathode that is additionally prone to vibration. The cell can is made of nickel-plated steel with the crimped rim having rounded cross-sections.

Wire bonds are designed for flat surfaces and bonding on the cells with rounded rims makes it even more challenging although later designs are now made flatter. The cell rim surface roughness is also inconsistent due to the crimping process and is prone to corrosion and electrolyte contamination.

Rough road conditions, rough handling or sudden acceleration/deceleration of the EV could cause wire fatigue and eventual breakage due to vibrations that are generated under such conditions. The result can be breakage in the heel region, the area between the bond and the span of the wire bond. This is a common cause of energy capacity loss in EV battery packs. Fig. 1 shows typical wire bonds interconnecting cylindrical battery cells together.

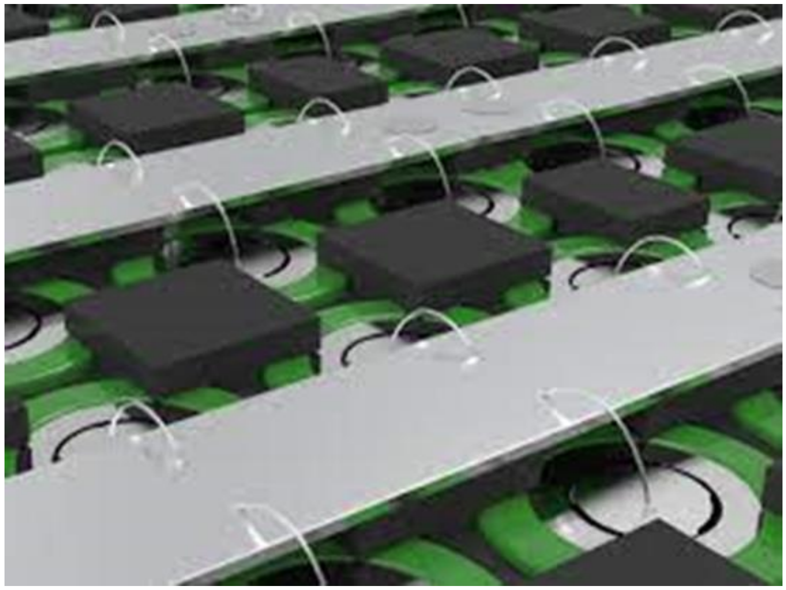

Fig. 1. Wire bonds interconnecting cylindrical battery cells.

Setup

The vibration tests were done using in-house-designed test equipment composed of a vibration generator, tables and an automatic timer (Fig. 2) installed in a Class 10K clean room, with temperature set at 20ºC and humidity at 50% RH.

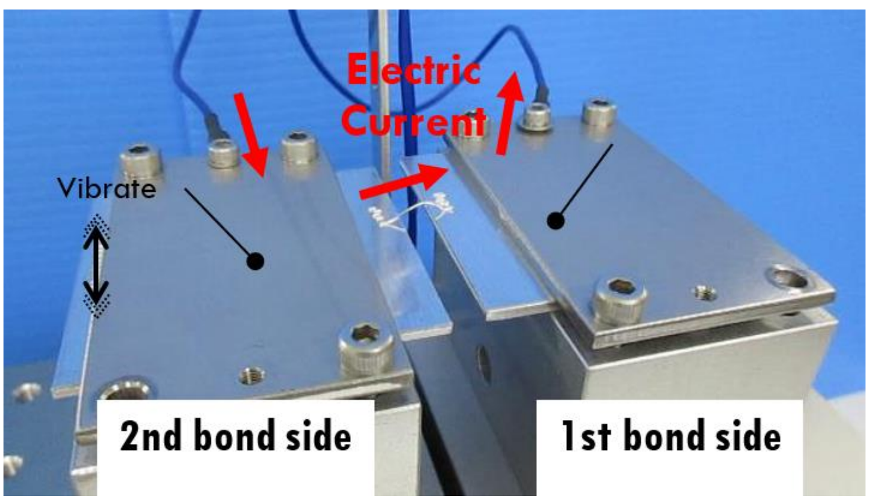

Fig. 2. Wire bond vibration tester developed in Tanaka Japan.

The vibration was done with a constant acceleration of 1.0 G with frequency variation from 10 to 70 Hz with corresponding amplitudes listed in Table 1. One test table was vibrated while the other was stationary. The automatic timer was wired such that it stops with the occurrence of a wire breakage.

$$A=(2\pi f)^2 \times D/1000 \quad (m/s^2)$$

A : Acceleration(m/s^2) D : Amplitude(mm) f : Frequency(Hz)

Table 1. Vibration frequency vs amplitude.

Frequency (Hz)	Acceleration (m/s^2)	Amplitude (mm)
10	1.0 G	2.484
12		1.725
21		0.563
25		0.397
50		0.099
70		0.051

Using a high-speed camera, bond-heel-crack propagation and wire breaks were recorded during the tests. Bond heels are where wire bonds typically fail. As expected, bond-heel cracks were initiated in proportion and direction to the vibration.

For example, in the vertical vibration test where the top motion was longer than the bottom motion with respect to the original plane of the vibrated bond, a crack initiated from the top portion of the wire first. This was followed by a bottom crack directly opposite it. Both cracks progressed towards each other across the cross-section of the wire until rupture.

A SEM image of a typical wire break is shown in Fig. 3 where a rupture line can be clearly seen roughly in the middle of the wire cross-section. This is typical of any metal fatigue failure where minute flaws caused by repeated mechanical stress grow and coalesce into multiple cracks culminating in eventual rupture.

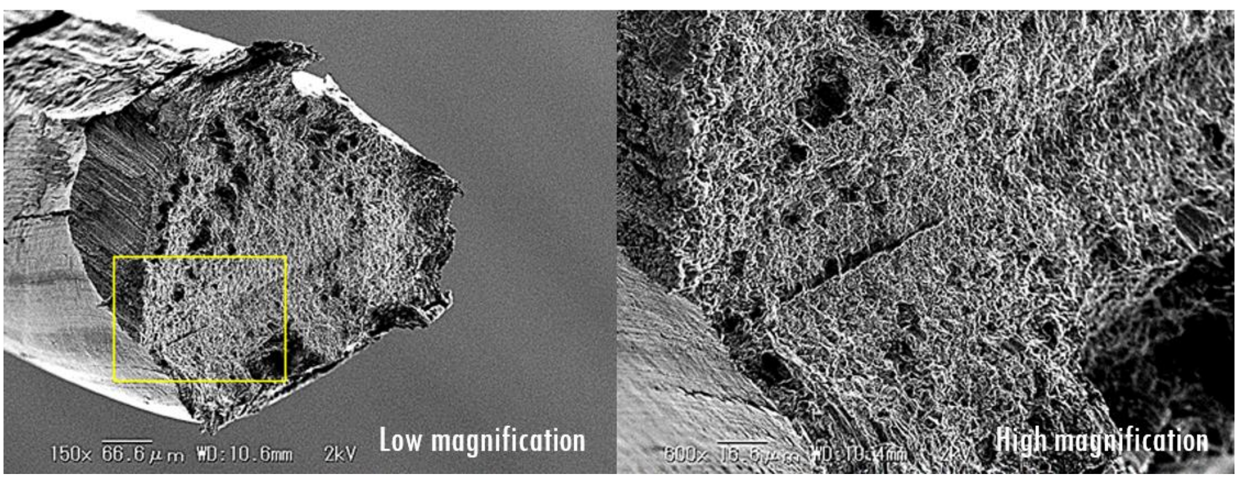

Fig. 3. Typical wire break. Note the rupture line near the center.

Fig. 4 shows the test wires made with either 20-mm long wire or ribbon bonds spanning two aluminum plates spaced 5-mm apart. The wire-bonded plates were then carefully clamped to the tables of the vibration tester; the first bond side of the wire was positioned on the stationary table and the second bond side was subjected to vibration during testing.

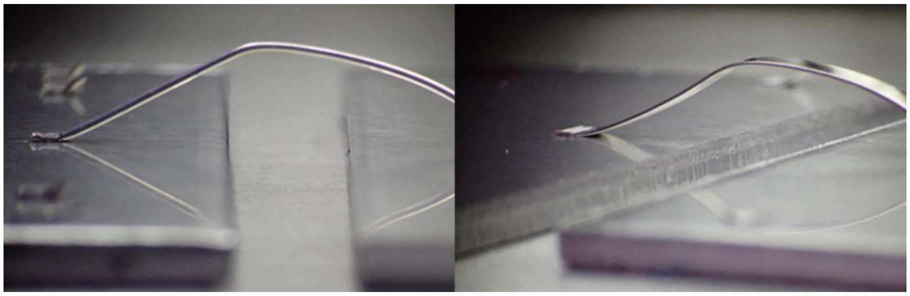

Fig. 4. Round wires used in the study were 400 microns in diameter (left) while the ribbons measured 2000 µm wide X 200 µm thick (right).

Results

The test conditions were designed to help understand the most significant factors that might contribute to broken wires in EV applications. This study consisted of five tests composed of various factors as listed in Table 2. Three vibration axes (X, Y, Z), four types of aluminum wires, three loop heights, and two wire shapes (round versus ribbon) were tested. The last test compared the performance of one bond versus entire wire vibration.

Table 2. Factors used in this study.

Test no.	Factor	Comparison
1	Vibration direction	Three directions (X, Y and Z)
2	Wire material	Four Al wires (4N and alloyed)
3	Loop height	Low, medium and high loop heights
4	Wire shape	Round vs ribbon
5	Bond vibration	Single versus both bonds

Test #1: Vibration Direction

The first set of tests was for the vibration of the second bond, with the first bond being stationary, in either X, Y, or Z directions using 400-µm diameter Al wires.

As shown in Fig. 5, there was a high incidence of failure in the X direction test where the wire bond was basically stretched. This is similar to a tensile stress of the wire bond and the weakest link—in this case the neck region of the vibrated second bond—typically ruptured after a minimum of a thousand cycles.

For the Y direction where the second bond was vibrated from side to side with respect to the first bond, failures varied from 1,000 up to one million cycles. Surprisingly, the same failure rate was observed during the Z direction vibration where the second bond was vibrated up and down with respect to the first bond.

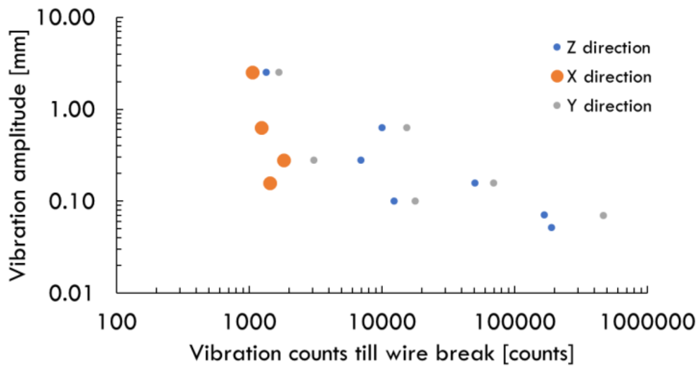

Fig. 5. Wire breakage versus vibration axes.

Test #2: Wire Material

In the second test, four aluminum materials made in 400-μm diameters with various tensile strength and electrical conductivity were compared as listed Table 3.

Table 3. Four aluminum materials tested.

No	Wire	Tensile strength (MPa)	Electrical conductivity (%IACS)
1	4N (99.99%) standard	50	63
2	Al alloy prototype-A	140	55
3	Al alloy prototype-B	130	50
4	Al alloy prototype-B	130	59

The results in Fig. 6 show no significant difference among the wires. One exception could be Al prototype Alloy A, where, if the amplitude was <0.1 mm, it showed improved vibration resistance nearing one million cycles as compared to the other wires.

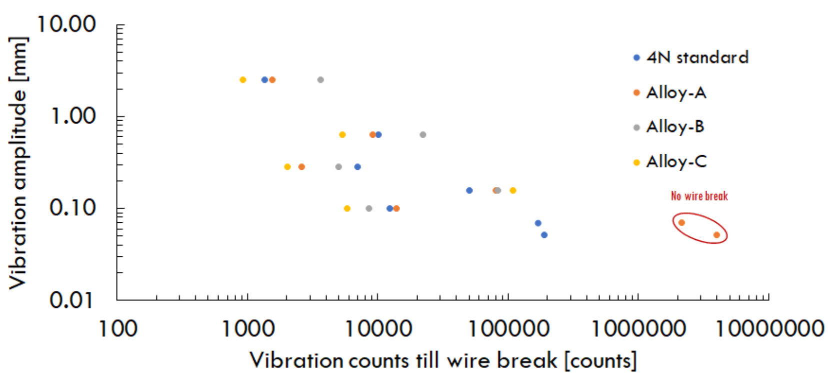

Fig. 6. Wire break versus Al material.

Test #3: Loop Height

Test wire bonds were made with three loop heights: 2 mm, 4 mm and 8 mm as shown in Fig. 7. As expected, the wire bonds with the highest 8-mm loop heights had slack that absorbed some of the vibration. The results shown in Fig. 8, indicate that the highest loops lasted up to one million cycles without breaking.

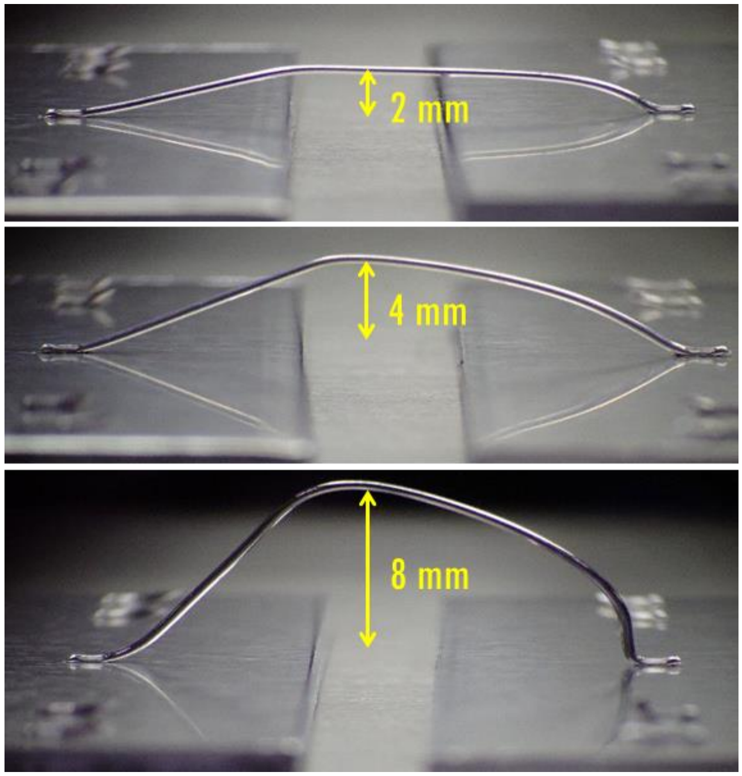

Fig. 7. Test wire bonds with different loop heights.

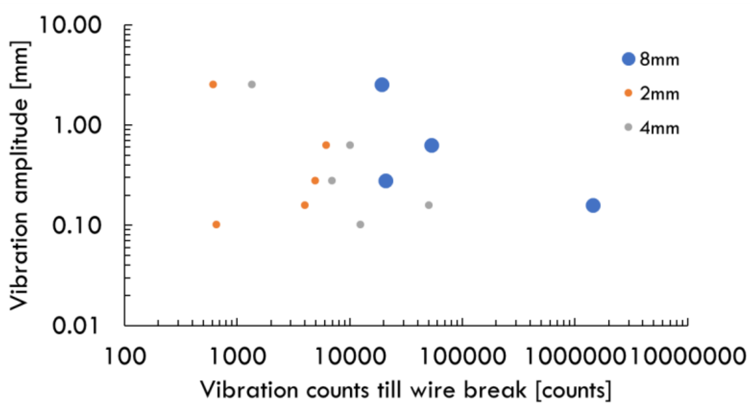

Fig. 8. Wire break versus loop height.

Test #4: Wire Shape—Round (400 µm) Vs. Ribbon Wire (2 x 0.2 mm)

Wire cross-section, either round or ribbon as shown earlier in Fig. 4, was also investigated in all X, Y, and Z axes. The results were significant but unsurprising.

In both Z-axis (vertical) and X-axis (longitudinal) vibrations, the ribbon bonds showed better vibration resistance than the round wire bonds as shown in Figs. 9 and 10, respectively. This is because of the ribbon bonds' inherent rigidity along its cross-sectional width. In the Y-axis (latitudinal) or sideways vibration, the same rigidity of ribbon wire bonds worked against it resulting in increased breakage frequency, shown in Fig. 11.

Test #5: Bond Vibration—First Bond Vs. Both Bonds (400 μm Al)

The fifth test determined the vibration resistance of a single bond versus entire wires. As expected, wire bonds break easily when only one of the bonds is vibrated. No breakage was observed if the entire wire was vibrated even for extended periods.

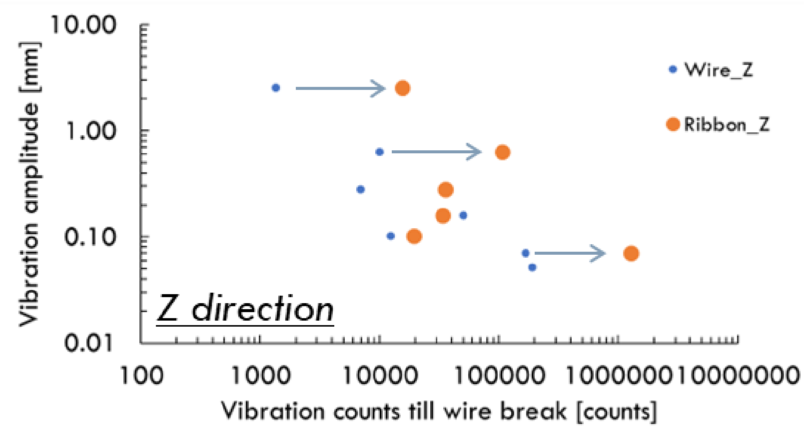

Fig. 9. Wire break versus wire shape, vibration in Z (vertical) axis.

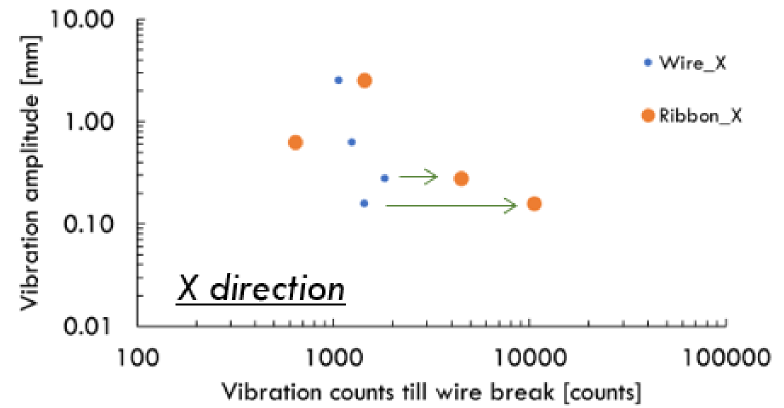

Fig. 10. Wire break versus wire shape, vibration in X (longitudinal) axis.

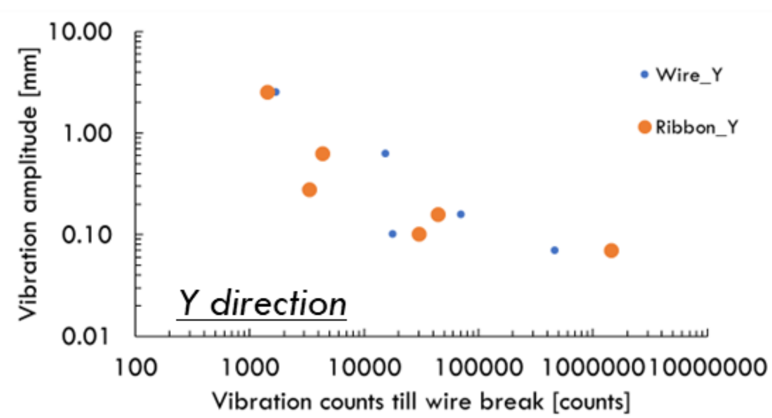

Fig. 11. Wire break versus wire shape, vibration in Y (latitudinal) axis.

Conclusions

From this study, we've learned that several aspects of wire bond design influence the vibration resistance of wire bonds in EV battery packs. First, we've observed that bond terminal (battery cell and busbar) rigidity with respect to wire bonds is important for enhanced vibration resistance. The more rigid the bond terminal, the greater the vibration resistance. We also learned that tensile or longitudinal vibration causes more failure than all other trajectories.

As expected, vibration resistance is directly proportional to loop height. Vibration resistance also increased with wire strength brought about by the difference in composition but only with amplitudes <0.1 mm. Finally, our tests revealed that ribbon wires exhibit better resistance than round wires in X and Z vibration directions.

References And For Further Reading

1. Videos of the vibration tests can be found at IMAPS2023 | TANAKA Precious Metals.
2. The subject of this article was originally presented at the IMAPS Wire Bonding Workshop on February 3, 2023 in San Diego, California. The presentation file can be accessed in Vibration Resistance Study of Wire bonds for EV Batteries.pdf

About The Authors

DodgieReigh Calpito is a business development manager for Tanaka Kikinzoku International (America). He has 20 years' experience in the assembly and packaging of semiconductors, MEMS, lasers and EV batteries. He holds six patents/pending patents and has co-written 12 publications on the subject of packaging. DodgieReigh can be reached at dodgie@ml.tanaka.co.jp.

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