Vibration Resistance and Durability of Wire Bonds for EV Batteries

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Abstract

Wire bond technology has long been used in semiconductor manufacturing because of its inherent flexibility, considered a major advantage over other interconnecting methods. With wire bonding, electrical interconnections or wire bonds are created between the silicon die and its leadframe or substrate using fine bonding wires made of gold, aluminum, copper, silver alloys or palladium-coated copper composites. These wire bonds are delicate though flexible, and in semiconductors, they are usually encapsulated by buffer materials such as resin or mold compounds, giving them a measure of durability and the ability to resist damage from vibration. But that measure of durability is lost in open-air applications including EV battery packs where there is no molding or encapsulation material to protect the wire bonds from the effects of vibration.

In this article, we look at ultrasonic wire bonding as it is currently used for the interconnection of cylindrical Lithium-ion (Li-ion) cells in EV battery packs, where such wire bonds are vulnerable to breakage due to vibration in part because they are not encapsulated. We look also at vibration tests of wire bonds using a.) test equipment developed for this study, and b.) five (5) kinds of comparison studies (vibration direction, material, wire shape, loop height, single bond or wire bond).

Introduction

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 which is supported by thin legs that are 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 rounded cell rim makes it even more challenging. 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 at the neck region between the bond and the span of the wire bond, a common cause of energy capacity loss in EV battery packs.

The goal of this study was to analyze the wire breakage problem and to offer some mitigation solutions to reduce or eliminate the failure.

Vibration Resistance and Durability of Wire Bonds for EV Batteries

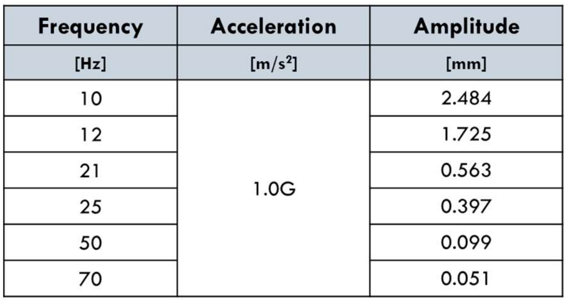
Set-up

The vibration tests were done using in-house designed test equipment composed of vibration generator, tables and automatic timer installed in a clean room, with temperature set around 20^{o}C and humidity around 50% RH.

For the vibration, given a constant acceleration of 1.0G, the test vibration frequency was varied from 10-70 Hz, providing inversely proportional amplitudes as listed in Table 1. One table is vibrated while the other is stationary. The automatic timer is wired such that it stops on the occurrence of 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)



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

Table 1. Vibration frequency vs amplitude.

Using a high-speed camera, crack propagation and wire breaks were recorded during the tests. As expected, cracks are initiated in proportion and direction to the vibration. For example, in the vertical vibration test where the top motion is longer than the bottom motion with respect to the original plane of the vibrated bond, a crack initiates from the top portion of wire first. This is followed by a bottom crack directly opposite it. Both cracks progress towards each other across the cross-section of the wire until rupture. A SEM image of a typical wire break is shown in Figure 1.

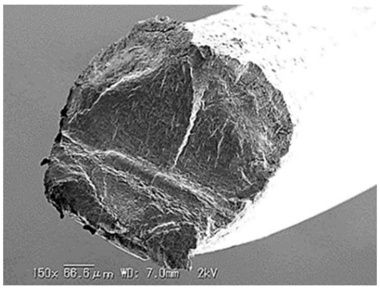


Figure 1. Typical wire break. Note rupture line near center.

Vibration Resistance and Durability of Wire Bonds for EV Batteries

Figure 2 shows the test wires made with either 20mm long wire or ribbon bonds spanning two aluminum plates spaced 5mm apart. The first bond side being stationary and the second bond side subjected to vibration during testing.

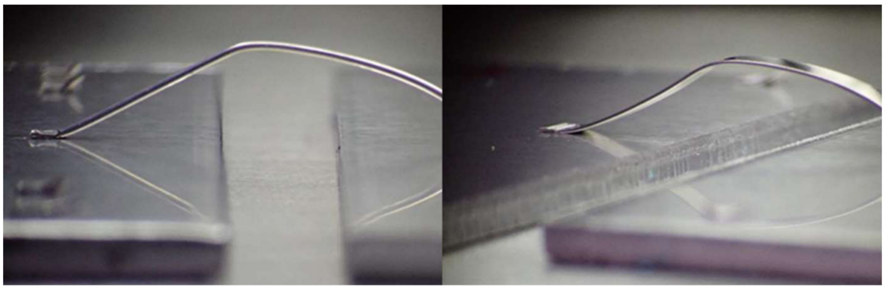


Figure 2. Round wires used in the study are 400 microns in diameter (L) while the ribbons measure 2000um X 200um (R).

Results

The test conditions were designed to help understand the most significant factors that might contribute to broken wires in EV applications. The study consists of five tests composed of various factors as listed in Table 2 below. Three vibration axes (X, Y, Z), four types of aluminum wires, three loop heights, two wire shapes (round vs ribbon) were tested. The last test compared the performance of one bond vs 1 wire vibration.

Test No	Factor	Comparison
1	Vibration Direction	Three (3) direction (X, Y and Z)
2	Wire Material	Four (4) Al wires (4N and alloyed)
3	Loop Height	Low, Medium and High loop heights
4	Wire Shape	Round vs Ribbon
5	Bond Vibration	Single vs Both bonds

Table 2. Factors used in the study.

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 axes with respect to the wire bond length using 400um diameter Al wires.

Vibration Resistance and Durability of Wire Bonds for EV Batteries

As shown in Figure 3, in the X direction test where the wire bond is basically stretched, there is a high incidence of failure. This is akin 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 at least a thousand cycles.

For the Y direction where the second bond is 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 is vibrated up and down with respect to the first bond.

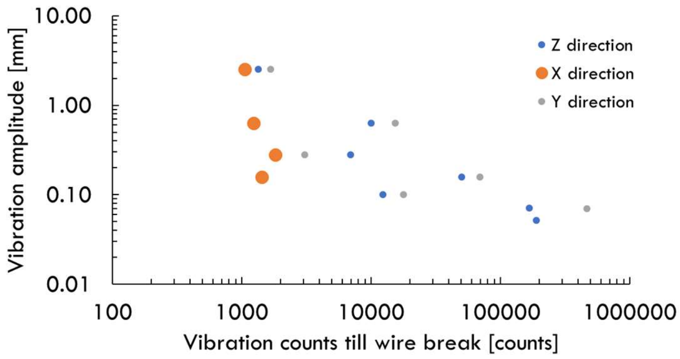


Figure 3. Wire breakage vs. vibration axes.

Test #2: Wire Material

In the second test, four aluminum materials made in 400um diameters with various tensile strength and electrical conductivity were compared as listed in the table below:

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-C	130	59

Table 3. Four aluminum materials tested.

The results shown in Figure 4 show no significant difference among the wires except perhaps for Al prototype alloy no. 2 where, if the amplitude <0.1mm, it showed improved vibration resistance near one million cycles as compared to other wires, including the standard production wire.

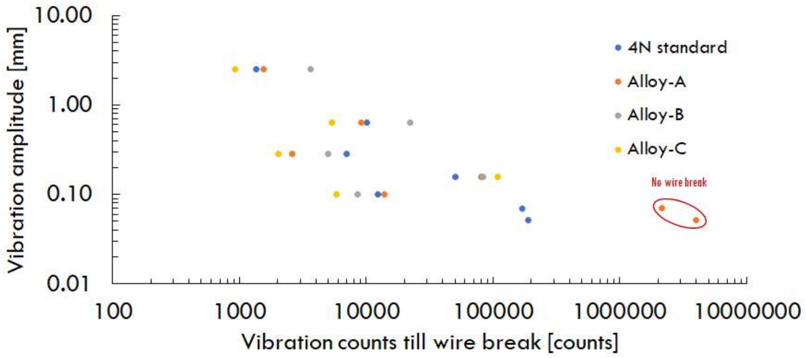


Figure 4. Wire break vs. Al material.

Test #3: Loop Height

Test wire bonds were made with three loop heights, 2mm, 4mm and 8mm. As expected, the wire bonds with the highest 8mm loop heights had slack that absorbed some of the vibration as shown in Figure 5, some of which even lasted up to one million cycles without breaking.

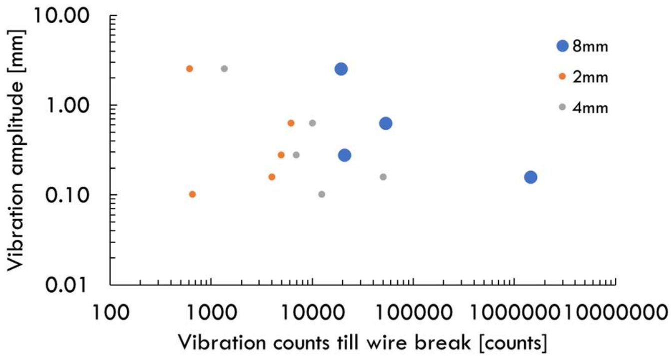


Figure 5. Wire break vs loop height.

Test #4: Wire Shape: Round (400um) vs Ribbon Wire (2x0.2mm)

Wire cross-section, either round or ribbon, was also investigated in all X, Y, and Z axes which resulted in significant but unsurprising results. In both Z- and X-axis vibrations, the ribbon wire bonds showed better vibration resistance than the round wire bonds because of the former's inherent rigidity along its cross-sectional width. In the Y-axis or sideways movement, the same rigidity of ribbon wire bonds worked against it resulting in increased breakage frequency.

Test #5: Bond Vibration: 1st Bond vs Both Bonds (400um Al)

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

Summary

The following are findings of the study:

- Bond terminals (battery cell and busbar) rigidity with respect to wire bonds are important for enhanced vibration resistance
- Loop height is directly proportional to vibration resistance
- Higher strength wire showed higher vibration resistance but only with amplitudes <0.1mm
- Ribbon wires showed better resistance than round wires in X and Z vibration directions