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JEDEC's Generation of Wire Bond Pull Test Methods to Address Pulling of Copper Wire Bonds

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Abstract

More than 50 years ago when the wire pull test method was initially added to Mil-Std 883, in Condition D of Method 2011, *Bond Strength (Destructive Bond Pull Test)*, the test procedure and minimum pull force values were based on pull testing of mostly ultrasonic wedge bonded aluminum and gold wires of just a few different diameters. The minimum pull force values from that original data were extrapolated to cover a much wider range of wire diameters for both gold and aluminum wires. Since the release of this test method the electronics industry has manufactured copper ultrasonic wedge bonds, widely adopted copper thermosonic ball bonding roughly 15 years ago, and even developed a niche market for silver thermosonic ball bonding. The industry also developed specialty bonds such as security bonds, reverse bonds also called "stitch on ball", and even multi-loop wires and ribbons. In all that time neither the test procedure nor the minimum pull force values in Method 2011 were reviewed to determine their appropriateness for these new materials or new types of bonds, even though the industry widely referenced the test method for all of them and thus, by default, accepted its use for all of them.

In late 2013, I led a working group within JEDEC's JC14.1 subcommittee, *Reliability Test Methods for Packaged Devices*, to update JEDEC JESD22-B116, *Ball Bond Shear Test Method*, to expand its scope to include the shearing of Cu ball bonds. It took the working group three years to address the necessary technical issues to ensure that the revised test method adequately addressed the shearing of copper ball bonds and propose minimum acceptable shear values. The working group produced a greatly improved document with drawings and images depicting the different shear fail modes of both gold and copper bonds and added several informative annexes to aid in the performing of the test method.

By 2018 it was apparent that none of the most commonly referenced wire pull test methods in the electronics industry had made any significant progress in updating their documents to include Cu wire bonds. Therefore, the JC14.1 working group agreed to work jointly with the JC-13.7 Subcommittee, *New Electronic Device Technology*, to create a new, wire pull test method document under JC14.1 that would be a companion to the JESD22-B116. This new document will use Method 2011, Conditions C and D as its basis, but expand on its scope to cover copper wire bonds, both ultrasonic wedge and thermosonic ball bonds. The new test method will describe the process for a ball pull test and a stitch pull test that are referenced for copper bonds by AEC Q006, *Qualification Requirement for Component Using Copper (Cu) Wire Interconnection.* The test method will also provide guidance on how to perform pull testing on several different bond types used today including reverse bonds, multi-loop bonds, and stacked die. The working group plans to propose minimum pull values for copper wire bonds which JC14.1 will reference in JESD47, *Stress-Test-Driven Qualification of Integrated Circuits*. After the joint working group completes its work, which is targeted for some time in 2022, JC13.7 would then be able to use the output of this working group to update Method 2011 Conditions C & D.

This paper will first briefly discuss the updates made to B116 to cover Cu wire bonds, but mainly focus on the work that has so far been completed by the joint working group, including a general outline of the proposed new document, JESD22-B120, *Wire Bond Pull Test Methods*.

Key words

Ball bond pull, copper wire, JEDEC, stitch bond pull, wire bond pull test method

I. Why Create a New Test Method

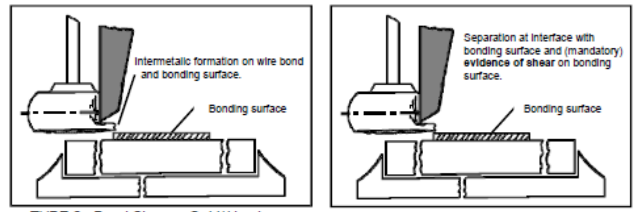
The JEDEC JC14.1 subcommittee, *Reliability Test Methods for Packaged Devices,* considered many factors and issues before it decided to generate its own wire bond pull test method. Copper (Cu) thermosonic wirebonding has been in mass production for more than 15 years and currently makes up a significant portion of all wirebonded packages manufactured today, but none of the widely referenced pull test methods have updated their test methods to accommodate the differences between the pulling of Cu wire bonds versus gold (Au) and aluminum (Al) wires bonds. Because of the difference in reliability concerns of Cu wire bonds vs. Au and Al, AEC now requires within its qualification standard Q006, *Qualification Requirement for Component Using Copper (Cu) Wire Interconnection*, that “Ball Pull” and “Stitch Pull” testing be performed, but neither Q006 nor any widely referenced pull test method currently defines how to perform those tests.

In addition to new wire alloys being used by the electronics industry, new types of bonds have also been widely adopted, but are yet to be acknowledged by the test methods. This includes reverse bonds (also known as stitch on ball) used for thin and stacked die package; security bonds to improve the strength of stitch bonds; and multi-loop (ultrasonically bonded) wires and ribbons that are used in high power devices. For these types of bonds guidance is needed so that there is consistency throughout the industry in how pull testing is performed.

JEDEC completed its revision of JESD22-B116, *Ball Bond Shear Test Method*, a few years ago, which expanded its scope to include the shearing of Cu ball bonds. As part of that revision significant updates were made to enhance diagrams and reference materials. It is the intention of the working group to generate a wire pull test method that will be a companion document to B116 in look and feel in the hopes that the electronics industry will quickly adopt it.

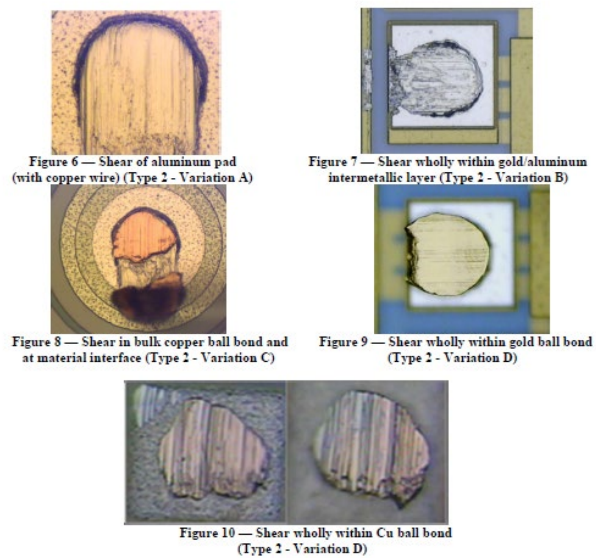
II. 2017 Revision of JESD22-B116

The revision of the ball bond shear test method, B116, to expand its scope to include Cu ball bonds took three years to complete. The Cu alloys used for thermosonic bonding form a very different intermetallic compound (IMC) with aluminum bond pads when compared to Au ball bonds on Al bond pads; and thus, have different failure surfaces when sheared. To assist users of the test method, new diagrams were created to describe these differences in the failure surfaces. To help users better classify the failure modes they observe during shear testing, optical images were added for all fail modes and all metal systems. Fig. 1 shows a few of the diagrams and Fig. 2 shows some of the optical images.



TYPE 2: Bond Shear – Gold/Aluminum Variation B – Separation wholly within intermetalic layer

TYPE 2: Bond Shear – All metal systems and surfaces, except Gold/Aluminum Variation B – Separation at bonding surface



Much of the three years was spent on determining the minimum acceptable shear values for Cu ball bonds. The test method had been created over 20 years previously and there was no documentation of what technique was used to create the values for Au ball bonds. In the end Cu bonds were made on test samples using decreasing force until “no stick” fails first occurred. Using those bonding parameters, shear testing was performed to identify what shear value was “at risk” for that specific ball diameter. This was repeated for multiple ball (wire) diameters. After analyzing the data, the working group observed that the values were within the same range as those of the existing values for Au ball bonds currently stated in the test method; thus, the working group proposed the same minimum shear values for both Au and Cu ball bonds. To be consistent with JEDEC policy, the minimum pull force was removed from the test method and put with other qualification criteria in JESD47, *Stress-Test-Driven Qualification of Integrated Circuits*.

The other significant change to B116 was the addition of several informative annexes to assist the user in the shearing of packages specifically with Cu wire bonds. These annexes provide guidance for performing shear testing on reverse bonds (commonly called "stitch on ball"), for performing shear testing on Cu ball bonds that first require removal of the encapsulation material (decapsulation), how to calculate the bond contact area for Cu ball bonds, which is required to calculate a value of shear force per unit area, and what to do when excessive Al splash prevents the shear tool from being placed at the proper height with respect to the ball.

III. Make-up of the Working Group

The working group for this new wire bond pull test method was based on a core group of device suppliers and users that revised the B116 document, but is open to all JEDEC JC14 and JC13 member companies, CE-12 and SAE member companies, shear tool and bond wire manufacturers, and any other interested organization. The working group currently has over 50 participants representing 25 companies and organizations.

IV. Scope of Proposed New Test Method

The new document, which will be given the document number JESD22-B120, used the Mil-Std 883, Method 2011 Conditions C & D as its starting point. The scope of the document will cover the pull testing of Au, Cu, and Ag (silver) thermosonically bonded wires that range in diameter from 15 to 76 microns; and Au, Cu, and Al ultrasonically bonded wires that range in diameter from 18 to 600 microns. The new test method will define the methods for the pulling of ball bonds and stitch bonds of thermosonically bonded wires. The document will also address the pulling of bonded wires with a hook and with a pull clamp. The test methods defined will be applicable for devices pre- and post-encapsulation. Lastly, guidance is being provided on how to perform pull testing on specialty bonds such as reverse bonds, multi-loop wires and ribbons, security bonds, and stacked die for which the wires may not be easily accessed for pull testing once the die stack is fully bonded.

V. Hook Placement

One significant technical item the working group needed to address was documenting the placement of the hook for each pull test; wire pull test (WPT), ball pull test (BPT) and stitch pull test (SPT). For the WPT there was some ambiguity on whether the hook should be placed at the midspan of the wire or at the apex of the wire loop. Similarly, for the BPT and SPT of whether the hook was placed at roughly 1/3 of the length of the wire away from the bond to be tested or as close as possible to the bond. For WPT the working group is proposing that the hook be placed at the approximate midspan of the wire for wires that are mostly horizontal, but for wires with an easily identifiable loop apex, the hook should be placed at the approximate midpoint of the wire midspan and the loop apex as shown in Fig. 3. For the BPT and SPT the hook is proposed to be placed as close to the bond as possible as shown in Fig. 4.

During working group meetings, it was mentioned on several occasions that the hook can be placed at a specific spot, but may slide along the wire as the hook is being pulled. For this reason, the test method does not specify an exact spot for the placement of the hook, but allows for it to be located over a length of wire shown in the diagrams by two boundary lines as shown in the diagrams in Figures 3 and 4.

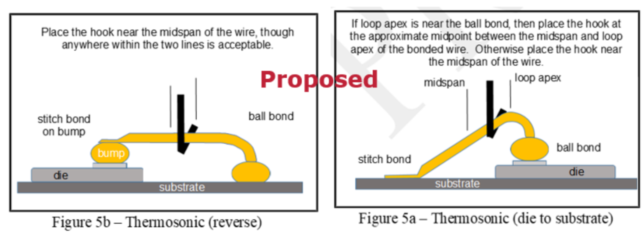


Fig. 3 – Hook placement for WPT on standard thermosonic bond and for reverse bond

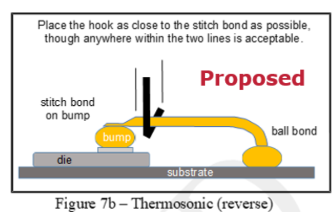


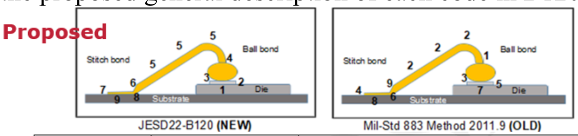
Fig. 4 – Hook placement for SPT on reverse bond

VI. Pull Failure Codes to be Renumbered

One major change being proposed in B120 is the numbering scheme that will be used for defining the failure code for where the bonded wire fails due to the pull test. Mil-Std 883, Method 2011 Condition D has a chaotic numbering scheme that appears to have been added onto over time as new fail modes were deemed to be important enough to be recorded. The issue with this scheme is that it was developed for standards bonds with one bond on a die and the other on a substrate, and thus, provides no guidance for how to apply the codes to other bond types (reverse bonds, die-to-die bonds, substrate-to-substrate bonds, and multi-loop bonds).

The new numbering scheme that is being proposed for pull failure codes will be able to be applied across all bond types. The new numbering scheme is applied in sequential order from the die through the bonded wire to the substrate with codes 1-3 for failures in the bond made with the die, codes

4-6 for breaks in the bulk wire, and codes 7-9 for failures in the bond made with the substrate/leadframe/post. Fig. 5 below shows a comparison of the proposed new codes compared with those Mil-Std 883 Method 2011.9 as well as the proposed general description of each code in B120.

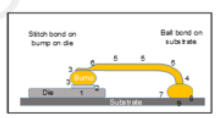


Failure code - per JESD22-B120	Failure code - per Mil-Std 883 M 2011.9	Description of failure code
0 (zero)	0 (zero)	Operator error or wire damaged/missing prior to test
1	7	Fracture or chip-out of die (includes cratering)
2	5	Lifted die metallization or failure within die metallization
3	3	Lift of bond from die metallization
4	1	Break in wire in the neckdown region of the first bond
5	2	Break in the span of the wire
6	9	Break in wire in the neckdown region of the second bond
7	4	Lift of bond from substrate/leadframe/post metallization
8	6	Lifted substrate/leadframe/post metallization
9	8	Fracture or lift of substrate/leadframe/post

Fig. 5 – General description of proposed pull fail codes compared to codes in Mil-Std 883 Method 2011.9

The new, numbering scheme was designed to be flexible so that it can be applied to each bond type which allows B120 to have a table for each bond type with a more descriptive definition for each failure code. Fig. 6 shows the specific failure code descriptions for reverse bonds, which first puts a bump (ball bond with wire removed) on the die bond pad and then puts a ball on the substrate and a stitch bond (2nd bond) on the bump. Note that failure code 3 can be applied to the stitch lifting off of the bump as well as the bump lifting off of the die bonding pad.

Code	Failure codes –reverse thermosonic bonds (ball on substrate, stitch [on bump] on die)
0	Operator error or wire damaged/missing prior to test
1	Fracture or chip-out of die including cratering (portion of dielectric material and possibly other layers remains attached to ball bond on die)
2	Lifted die metallization (partial or complete lifting of aluminum, copper, NiPdAu, or other die bond pad metallization plating) or failure within the metallization of the die bonding pad
3	Lift of stitch bond from bump (underlying ball bond) (some to no remnant of stitch on ball bond) or lift of bump (underlying ball bond) from die bonding pad (stitch still attached to bump)
4	Break in wire in the neckdown region above the ball bond in the heat affected zone (length equal to 2x wire diameter above ball)
5	Break in the span of the wire (from 2x wire diameter above the ball bond to just above the stitch bond)
6	Break in wire in the neckdown region of the stitch bond (portion of the wire deformed by the capillary, but not bonded to bump)
7	Lift of ball bond from substrate/leadframe/post metallization (separation between ball bond and substrate/leadframe/post pad metallization)
8	Lifted substrate/leadframe/post metallization (partial or complete lifting of copper land on substrate or plated metal on leadframe/post)
9	Fracture or lift of substrate/leadframe/post (portion of substrate material remains attached to ball bond)



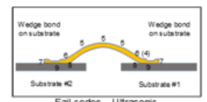
Fail Codes –Thermosonic (Reverse)

Proposed

Fig. 6 – Detailed pull failure codes for reverse thermosonically bonded wire

Fig. 7 shows the proposed table in B120 that provides the descriptive definitions of failure codes for wires bonded from one substrate/leadframe/post to another. This bond type does not come in contact with any die bonding pad, thus codes 1, 2, and 3 are not used. It also allows for the person performing the test to apply either code 4 or 6 to a break in the neckdown region of the first bond made, if the person performing the pull test has information that states which bond was made first. If the pull test were performed by the device assembler, the operator would likely know which bond was made first and thus would benefit by documenting this information. However, if a device user was performing the bond pull test, they would likely not have information of which bond was made first and thus the B120 recommends that code 6 be used for a break in the neckdown region for either bond.

Code	Failure codes – substrate to substrate ultrasonic bonds
0	Operator error or wire damaged/missing prior to test
1	Not applicable
2	Not applicable
3	Not applicable
4	Not applicable (Optional: If able to track which bond was made 1st and 2nd, code 4 may be used for a break in the wire in the neckdown region at the wedge bond above the 1st substrate/leadframe/post bonded (portion of the wire deformed by the bonding tool, but not bonded to the substrate/leadframe/post, and up to 2x wire diameter away from the wedge bond) and code 6 is for a similar break above the 2nd substrate/leadframe/post bonded)
5	Break in the span of the wire (more than 2x wire diameter away from either wedge bond)
6	Break in the wire in the neckdown region at the wedge bond on the substrate/leadframe/post (portion of the wire deformed by the bonding tool, but not bonded to the substrate/leadframe/post, and up to 2x wire diameter away from the wedge bond)
7	Lift of wedge bond from substrate/leadframe/post metallization (little to no remnant of stitch on substrate/leadframe/post)
8	Lifted substrate/leadframe/post metallization (partial or complete lifting of copper land on substrate or plated metal on leadframe/post)
9	Fracture or lift of substrate/leadframe/post (portion of substrate material remains attached to wedge bond)



Fail codes – Ultrasonic (Substrate to Substrate)

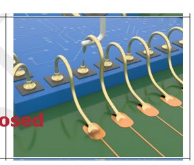
Proposed

Fig. 7 – Detailed pull failure codes for substrate to substate ultrasonically bonded wire

VII. Images for Failure Modes

In addition to the above mentioned written description of each failure code this document will also provide the user illustrations of each failure mode to ensure that they assign the correct failure code. The illustrations depict a hook pulling tool on a thermosonically bonded wire, but are general in nature; thus, they are applicable to the failure modes for both thermosonic and ultrasonic bonds as well as hook pull and clamp pull methods. Fig. 8 shows two failure modes.

Fail Code 4
Break in wire in the neckdown region of the first bond



Fail Code 8
Lifted substrate/leadframe /post metallization

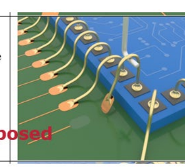


Fig. 8 – 3D images of two failure modes for pull tests

We have gathered detailed optical images in an attempt to guide the user in assigning the correct failure code for fails at or near thermosonic stitch bonds. For Cu stitch bonds is not easy to discern where code 6 ends (break in wire in neckdown region) and code 7 begins (lifted stitch bond). Fig. 9 shows a progression of breaks near or at the stitch bond.

Fig. 9 Progression of fails near or within the stitch bond with

failure codes 6 and 7 assigned appropriately

VIII. Multiple annexes to provide guidance

Several informative annexes are being generated for this document. Annex A will provide special guidance when performing pull testing on stacked bonds (reverse, security, and others), for process development and during production. For security bonds and other stacked bonds, it is recommended that during process development pull testing (WPT, BPT and/or SPT) be performed to ensure that the bonding parameters are optimized for the first bonded wire, as well as the 2nd bonded wire. For pull testing of production assembly lots only pull testing of fully assembled stack bonds is recommended.

Annex B will provide guidance for wire pull testing of decapsulated devices and is based on a similar annex in B116. The automotive industry requires that pull testing be performed on Cu wire bonds after stress testing, however, when Cu bond wires were first being qualified it was shown that the etchants used to decapsulate packaged devices severely corroded the copper alloy wires and new etching solutions and techniques had to be developed. When silver alloy wires were first being qualified, similar concerns were also seen. For this annex in B120 additional information is being included so this annex is being broken down into three subclauses. The topics include a warning about performing ultrasonic cleaning once the bonds are exposed, concerns with the decapsulation processes for devices with copper and silver wirebonds, and the concern of undercutting bonds due to over etching of the silver plating on leadframes.

Annex C discusses the difference in the numbering scheme between B120 and Mil-Std 883 Method 2011.9. The image in Fig. 5 is part of this annex. The illustrations in Fig. 8 and the optical images in Fig. 9 are part of Annex D which also includes additional guidance for assigning codes 6 and 7. The location of where a break in the neckdown region of a stitch bond (code 6) ends and where a stitch lift (code 7) begins varies based on wire material and the bonding surface (both base material and finish). Fig. 10 and Fig. 11 are SEM images showing the differences in shape and location of the metallurgical bond for two stitch bonds.

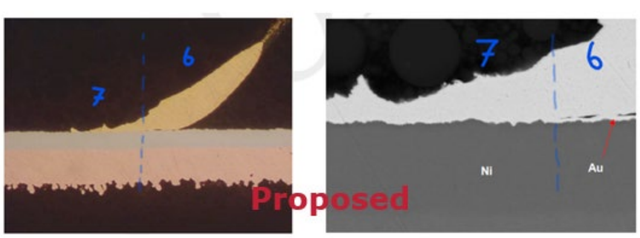


Fig. 10 – Au stitch bond on organic substrate with NiAu plated Cu land

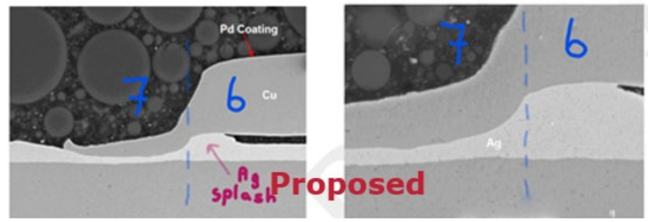


Fig. 11 – Pd coated Cu stitch bond on Ag plated Cu leadframe

Annex F is being proposed to discuss issues with pull test that can affect the wire pull force value and the failure mode. Hook placement along the length of the wire as well as the angles formed between the wire and the substrate of each bond as with wire is being pulled.

Annex E is being proposed to provide guidance regarding the minimum pull force specification values versus process control requirements. The intention of the minimum pull force values stated in qualification standards is to identify unacceptable bonds, e.g., ones that would likely fail during the life of the device. The intent of wire bond pull testing is not to measure a wire's mechanical properties but the strength of the bonds made. Thus, the ideal fail would be to have a failure code of 5, a break in the span of the wire, which implies that the bonds are stronger than the wire. Since the majority of the fails in production tests are code 5, the nominal pull force values are significantly higher than the minimum required pull force values. For this reason, the focus during the wire bonding process should be on good statistical process control (SPC) and maverick product management. Any pull tests results that are not assigned a code of 5 may indicate an issue with the bonding process or the materials used. Failure codes 4 and 6 may indicate an issue with the wire material or the bonding process/tool. Failure codes 1-3 and 7-9 may also indicate an issue with the wire or the bonding process/tool, but also the bonding surface. For these reasons any pull result that is not assigned a code of 5 and the pull value is outside its normal distribution (an outlier product as defined in JESD50, *Special Requirements for Maverick Product Elimination and Outlier Management*) it should be evaluated for root cause and the necessary corrective actions be implemented.

IX. Minimum acceptable pull force value for Cu alloy wire

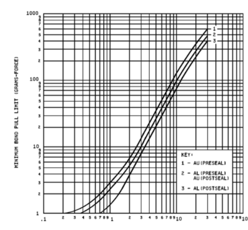
As the Mil-Std 883 Method 2011.9 Condition D includes the minimum pull force values for gold and aluminum bond wires, the working group's other main task was to determine what those values should be for bonds made with Cu alloy wire. The values for Al and Au wires were generated over 50 years ago mostly from ultrasonic Al and Au wires of only a few different diameters. Since that initial release, they were never updated or verified for new wire alloys, bonding surfaces, bond types, or bonding techniques. This includes the wide adoption of Au, Cu, and Ag thermosonic bonding; Cu ultrasonic bonding; ribbon bonds; and the full range of wire diameters covered in the scope of that test method. The working group upon learning how the pull force values have been applied to a much larger scope of bonds than for what it was originally developed, decided that it made no sense to propose and validate new minimum pull values to cover Cu thermosonic bonds. To have done that, the working group would need to perform testing on all of the pertinent variations of commonly used bonding surfaces and Cu alloys used throughout the electronics industry.

One of the tasks the working group did was to gather information about the many commonly used Cu, Au, Al, and Ag alloy wires (coated and bare) as well as Al ribbons used today for thermosonic and ultrasonic bonding. The working group did not find any "across the board" correlation between wire mechanical properties and wire base metals, though a few generalizations were observed. On average elongation was greatest for Cu, then Au, and least for Al alloy wires, and with respect to breaking load bare Cu < Au < coated Cu < Al. We found that some Cu alloys have very high purity at 99.999% pure (5 nines - 5N), though 4N and 2N purity wire for all base metals is much more common for Au, Cu, and Al wires; while Ag wires ranged from 88% to 99% Ag. There appeared to be a trend of mechanical properties across all base metals by wire manufacturer, with some manufacturers producing wires with higher hardness and higher breaking load than others of similar purity of base metal.

With all this variation, we either had to accept that the original minimum pull force should be applied across all wires used today, or else we would have to design several multi-variable studies to determine the appropriate minimum pull force value for each type of wire, bonding surface, bond type, and bonding technique. The working group acknowledged that the industry has been using the Au minimum pull force values for Cu wires with no significant issue for nearly 15 years. Therefore, B120 will propose that Cu wires, both Pd coated and bare will use the Au minimum pull force values. There is not enough experience with Ag wire within the working group to make the same proposal for Ag wire for the initial release of B120.

As the core of the working group is JC14 members and B120 will be published and maintained by the JC14.1 committee, this proposal will be stated in JESD47 for wire pull testing of product prior to encapsulation (equivalent to the term "pre-seal" in Mil-Std 883). As the working group also has JC13.7 members, the working group will also propose minimum pull force values for Cu wire bonds for post-encapsulation (post-seal) so that the JC13.7 members can take back both sets of values to MIL/DLA representatives to serve as the basis for future improvements and changes to Mil-Std 883 Method 2011 Condition D.

In reviewing the minimum pull force values in Method 2011.9 the working group had to address the discrepancy in the minimum pull force values for 1.25 and 1.3 mil wires in the table versus the chart. The table states that both wire diameters have the same pull values, but the graph conveys different values. To get around this issue, since 1.25 mil Au wire is not common, no value will be provided in the table in JESD47; and similarly, 1.3 mil Al wire is not common so the table will not provide a value for it. As the graph is log-log, the working group found that it was difficult for two persons to consistently obtain the same minimum pull force value for a given wire diameter, especially for larger diameter wire. Therefore, JESD47 will provide a table (see Fig. 12) of minimum pull force values for 17 commonly used wire diameters which is much more than the 5 values listed in Method 2011.9.



Wire Diameter		Minimum bond strength (grams force) (pre-encapsulation)	Minimum bond strength (grams force) (pre-encapsulation)
(microns)	(mils)	**Au & Cu**	**Al**
15	0.6	1.7	Out of scope
18	0.7	2.0	1.5
20	0.8	2.3	1.8
25	1.0	3.0	2.5
30	1.2	3.6	(N/A)
32	1.25	(N/A)	3.0
33	1.3	4.0	(N/A)
38	1.5	5.0	4.0
50	2.0	6.8	5.5
75	3.0	15	12
100	4.0		
125	5.0	36	27
200	8.0		
250	10	140	98
300	12		
380	15	250	200
500	20	360	280

Proposed

Fig. 12 – Graph in Method 2011.9 & JESD47 proposed table

X. Conclusion

The working group is getting close to completing the generation of the new B120 test method with targets to complete the body of the test method by the time this paper is presented and the annexes by the end of this year. A similar target for updating JESD47 with a table of minimum acceptable pull values is also set for the end of this year. These targets will allow for JEDEC members to review and vote on the initial drafts for both documents after its meetings next January. It is hoped that the documents can complete all voting and comment resolutions by the summer of 2022 and be published together in the fall of 2022.

The working group members strongly believe that the proposed B120 test method will provide a very needed benefit to the electronics industry by providing uniform instruction and guidance in the pull testing of all wire bonded devices.

Acknowledgment

Jeff Jarvis, vice-chair of JEDEC JC13.7 and Ife Hsu, chair if JEDEC JC14.1 for their review of this paper and presentation.